Novel Flow Sheet for Low Energy CO_2 Capture Enabled by Biocatalyst Delivery System

Preliminary Techno-Economic Assessment Report

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Principal Authors:
John Reardon (PE) and Alex Shaffer of Akermin Inc, and Vladimir Vaysman (PE) of WorleyParsons

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Submitting Organization:
Akermin, Inc.
1005 N. Warson Road, Suite 101
St. Louis, MO 63132

Subcontracting Organizations:
WorleyParsons
2675 Morgantown Road #1
Reading, PA 19607

Disclaimer

Abstract

This report documents a preliminary Techno-Economic Assessment (TEA) for processes utilizing Akermin's second generation biocatalyst delivery system to enhance AKM24, a non-volatile salt solution for CO_2 capture. Biocatalyst enhanced AKM24 offers the potential to reduce the cost of CO_2 capture in flue gas applications due to its improved equilibrium and stoichiometric properties that result in double the absorption capacity relative to previously demonstrated biocatalyst enhanced solvents. The study assumes a new supercritical pulverized coal fired power plant with a net output of 550 MWe after 90% CO_2 capture and uses the June 2011 cost basis (August 2012 update of Bituminous Baseline Study, or BBS). Power plant modeling, capital cost review, and economic calculations were provided by WorleyParsons. Rate-based CO_2 capture process modeling and equipment sizing was performed by Akermin using AspenPlus® V8.4, customized to accurately predict thermodynamics, kinetics, and physical properties of the AKM-24 solvent based on available laboratory data. Equipment capital costs were estimated using Aspen Process Economic Analyzer™ which compared well with published baseline cost estimates. Quotes of equipment costs and power consumption for vacuum blower and CO_2 compression equipment were also provided by Man Diesel & Turbo.

Three process scenarios were examined for Akermin biocatalyst enhanced solvent systems including: Case-1A: an absorption-desorption system operated with a reboiler pressure of 0.16 bara (60°C); Case-2A: an absorption-desorption system with moderate vacuum assisted regeneration at 0.40 bara (80°C); and finally, Case-2B: a conventional absorption-desorption system with near atmospheric pressure regeneration at 1.07 bara (105°C). The estimated increases in cost of electricity (ICOE) for these cases were \$58.1/MWh, \$47.3/MWh and \$46.4/MWh, respectively. Case 2B had the best results for this analysis achieving an estimated 30% reduction in ICOE relative to the NETL Case 12 (v2) baseline of \$66.3/MWh ICOE. Likewise, Case-2B achieved capture costs of \$53.0/tCO_2 and 65.7/tCO_2 avoided, which equates to 20.2% and 31.4% savings relative to the Case 12 baseline (\$66.4/tCO_2 and \$95.9/tCO_2 avoided). While Case 2A and 2B have similar results, Case 2A requires further development. Focus on Case 2B is recommended for this project because its cost performance is closest to the DOE goals, and has it has the best potential to achieve a successful demonstration at the next scale.

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1. EXECUTIVE SUMMARY

This report details the findings of a preliminary Techno-Economic Assessment (TEA) completed to evaluate Akermin's 2nd Generation Biocatalyst Delivery System (BDS). Work completed during this project fulfills the successful completion of Task 4 for DOE project award DE-FE0012862. All economic comparisons were completed on equivalent basis as that described in the Bituminous Baseline Study (BBS) [2] with updated costing applied (June 2011 basis) from the report "Updated Costs (June 2011 Basis) for Selected Bituminous Baseline Cases [3]." The benchmark case, Case 12, is a 550 MWe net supercritical pulverized coal-fired (SCPC) power plant equipped with a 30% monoethanolamine (MEA) CO_2 capture system.

The three cases proposed by Akermin for evaluation in this Preliminary TEA are labeled as follows: (1A), (2A), and (2B). Case labels indicate if the capture process is approximately "isothermal" (Case 1), or if some amount of "temperature swing" (Case 2) occurs between the absorber and stripper.

All Akermin cases include Akermin's proprietary biocatalyst in what is called a "biocatalyst delivery system" (BDS). However, the sub-case label indicates the specific configuration of the biocatalyst delivery system where (A) indicates that no separation system is required with biocatalyst circulated through the entire absorber-stripper system, and (B) indicates that a biocatalyst recovery system is included to isolate biocatalyst within the absorber only.

WorleyParsons (WP) served several key functions in this TEA. First, WP conducted all power plant steam cycle modeling using *GateCycle™* software and developed a capital cost estimate for the power plant. WP also reviewed and verified capital cost estimation for the CO_2 capture unit and gave inputs on major equipment selection. WP also provided technical advisement on practical considerations for steam extraction, capital cost estimation using Aspen Process Economic Analyzer™, and certain major equipment selection including heat exchangers, vacuum blowers, and CO_2 compressors. Gross power, electrical load for CO_2 capture, and net plant efficiency results are summarized in Exhibit 1-1 below:

Exhibit 1-1: Summary of Overall Power Plant Efficiency with CO_2 Capture

	Net Power (MWe)	Gross Power (MWe)	Incremental Electrical Load with Capture (MWe)	Savings Relative to NETL Case-12 (%)	Net Plant Efficiency (% Fuel HHV)
NETL-11	550.0	580.4	--	n/a	39.3%
NETL-12	550.0	662.8	82.4	--	28.4%
Case-1A	550.0	694.2	113.8	-38.1%	31.3%
Case-2A	550.0	662.8	82.4	0.0%	32.3%
Case-2B	550.0	649.9	69.5	15.7%	32.5%

Case 2B has the lowest incremental electrical load. Notably the incremental load for Case-2A is similar to that of NETL-12, but the equivalent work for steam regeneration is less in this case (due to lower steam turbine extraction temperature) which results in fuel savings and higher net plant efficiency.

Akermin's process modeling for the CO_2 capture unit was performed using *AspenPlus® V8.4*, which had been programmed and validated for the AKM24 solvent based on a range of laboratory data. *Aspen Process Economic Analyzer*™ was used to develop bare erected capital cost (BEC) estimates for the CO_2 capture unit, and results were reviewed by WP. Total Plant Costs for Akermin cases include 9.2% EPC fees, a 30% process contingency, and a 26.2% project contingency. The Total As-Spent Costs (TASC) includes escalation and interest on debt for the construction period equivalent to the bituminous baseline study (BBS). Summary capital cost estimates for the CO_2 capture systems are presented in Exhibit 1-2 below including vacuum blowers where applicable, but excluding CO_2 compression (consistent to Case-12 presentation).

Exhibit 1-2: Capital cost summary for the CO_2 capture unit & power plant

	CO_2 Capture Unit				SCPC Power Plant + CO_2 Unit	
	BEC ($MM, 2011)	BEC Savings (%)	TASC ($MM, 2011)	TASC Savings (%)	TASC ($MM, 2011)	TASC Savings (%)
NETL-11	n/a	n/a	n/a	n/a	n/a	n/a
NETL-12	$326.1	0%	$834.4	0%	$2,753	0%
Case-1A	$302.7	7.2%	$822.5	1.4%	$2,659	3.4%
Case-2A	$216.0	33.7%	$604.6	27.5%	$2,392	13.1%
Case-2B	$205.8	36.9%	$593.1	28.9%	$2,369	13.9%

Sensitivity studies were performed to quantify impact of critical design assumptions on the cost of electricity (COE), see conclusions 9, 10 and 11. The key findings in Exhibit 1-3 below have been updated to reflect most current information including cost and energy estimates for vacuum blowers and CO_2 compressors provided by *MAN Diesel & Turbo* in December 2014. A summary table below presents the key results for cost of electricity (COE), increase in cost of electricity (ICOE) relative to no capture reference case, cost of capture (per metric ton), and avoided cost of capture.

Exhibit 1-3: Key Results Table, Executive Summary

	COE ($/MWh)	ICOE ($/MWh)	% ICOE	Savings (%)	Capture ($/t$CO_2$)	Savings (%)	Avoided ($/tCO2)	Savings (%)
NETL-11	80.95	--	--					
NETL-12	147.3	66.32	81.9%	--	66.45	--	95.98	--
Case-1A	138.9	58.00	71.7%	12.5%	64.11	3.4%	82.65	13.8%
Case-2A	128.3	47.32	58.5%	28.6%	54.04	18.6%	67.12	30.0%
Case-2B	127.3	46.34	57.3%	30.1%	52.99	20.2%	65.73	31.5%

Summary Conclusions:

1) Akermin Case 2B achieved the best economic performance of all cases.
2) Case-2B achieved 15.7% savings in gross power penalty relative to NETL Case-12.
3) Case 2B reduced the efficiency penalty from 10.9 (Case 12) to 6.8 percentage points.
4) Case 2B achieved 37% savings in Bare Erected Costs (BEC) for the CO_2 capture unit, (including vacuum blower but excluding CO2 compressor).
5) Case 2B achieved approximately 29% lower capital cost penalty (TASC basis) for the CO_2 capture unit relative to Case-12, including CO_2 compression.
6) Case-2B achieved 30% lower electricity cost penalty compared to NETL Case-12.
7) 57% ICOE achieved in Case-2B relative to no capture (NETL Case 11), notably better than the 82% ICOE for Case-12 but short of the long-term DOE goal of 35% ICOE.
8) Case 2B achieved 31% lower avoided cost of capture and 20% lower cost of capture relative to Case-12 baseline.
9) Case 2B includes equipment and energy costs for the biocatalyst recovery system; sensitivity study reveals the importance of technology selection to minimize costs.
10) All AKM24 cases are relatively insensitive to solvent cost, because loss rate are assumed to be quite low with the non-volatile salt system.
11) The study assumes the biocatalyst half-life is 12-months (1 year), a future development target, and concludes biocatalyst cost contribution to COE is relatively minor.

Case-2B in this study assumes a biocatalyst recovery system based on review of multiple technical options, considering capital cost and operating costs. This study also assumes a 12-month biocatalyst half-life, which is a long-term development goal. The biocatalyst cost under these assumptions equated to $0.79/t$CO_2$, $0.46/t$CO_2$, and $0.43/t$CO_2$ for Cases 1A, 2A and 2B respectively. A sensitivity study found that the biocatalyst contribution to CO_2 capture costs remained relatively insignificant until the half-life was reduced below 3-months.

Based on the conclusions of this preliminary TEA, Akermin will focus development on the Case-2B configuration. Besides biocatalyst development to maximize long-term performance, the successful development and demonstration of an efficient, low energy, and low cost biocatalyst recovery system in this project is essential to successful demonstration of this technology at the next scale.

2. INTRODUCTION

The overall goal of this three year project, DE-FE0012862, is to develop Akermin's next-generation Biocatalyst Delivery System (BDS) to reduce the cost CO_2 capture from flue gas using a non-volatile salt blend (AKM-24 solvent) while demonstrating progress towards the DOE economic goals of (a) 90% CO_2 capture with less than 35% increase in cost of electricity, or (b) less than 40/tonne CO_2 captured. This report has been prepared as a preliminary techno-economic assessment (TEA) to screen three possible process cases, each of which are described in more detail in the body of this report.

The results of this "Preliminary TEA" study will be used measure the Akermin technology relative to the DOE goals and to mark progress relative to key performance metrics set forth for this project. These Preliminary TEA results will also be used as a guiding assessment to help prioritize efforts for this project going-forward. Albeit preliminary, the results are sufficient to discount certain process options that will not be pursued in the final TEA while prioritizing others. A follow-up 'Final TEA' will explore further cost reduction opportunities and include feedback from bench-unit field testing.

Akermin has the following key process and economic performance objectives:

- Demonstrate a second generation biocatalyst that has lower production costs, is more readily scaled-up, and enables *on-stream* catalyst replacement.
- Deploy a non-volatile, environmentally-benign AKM-24 solvent that doubles CO_2 absorption capacity.
- Modify an existing 30 Nm^3/hr bench unit to incorporate a preferred process flow scheme and biocatalyst delivery system, considering the results of this preliminary economic analysis.
- Optimize process cases to achieve equivalent-work that is less than 220-kWh/tCO_2 (including parasitic impacts of steam extraction and all electrical parasitic loads).
- Demonstrate that capital costs can be reduced by at least 20%.
- Demonstrate cases with potential to achieve at least 30% reduction in cost of CO_2 capture relative to NETL Case 12 v2.
- Demonstrate integrated system performance during a six-month field test at the NCCC using actual coal combustion flue gas.

The above goals are based on incorporating process and solvent-related advances with Akermin's second generation biocatalyst delivery system. These features will be integrated into an existing bench unit and then tested with coal-combustion flue gas at National Carbon Capture

Center (NCCC), with target time-on-stream exceeding 2000 hours. The existing bench-scale unit was designed under DOE Cooperative Agreement DE-FE0004228 to remove 90% CO_2 from 30 Nm^3/hr coal flue gas assuming 15.9% CO_2 (dry).

This document presents the results of a preliminary techno-economic assessment (TEA) of Akermin's next-generation BDS with processes incorporating the advanced AKM24 solvent. These studies are conceptual in nature and include efforts by WorleyParsons that were performed to the recognized engineering principles and practices appropriate for conceptual engineering work. This study report may not be relied upon for detailed implementation or any other purpose not specifically identified within this study report.

The preliminary TEA is conducted in accordance with the guidelines provided in SOPO [1]. The evaluation scope includes:

- Developing an evaluation basis that defines essential technical and functional requirements to establish a conceptual design for a nominal 550 MWe (net), greenfield, pulverized coal (PC) power plant that includes post-combustion CO_2 capture technology. The approach is identical to that used for NETL Case 12, supercritical PC with CO_2 capture as presented in the Bituminous Baseline Study (BBS) for post-combustion capture technologies [2];
- Comparative evaluation of the power plant design scenarios with Akermin CO_2 capture system alternatives, including developing heat and mass balances (HMB) diagrams and estimating plant performance;
- Estimating capital and O&M cost; and
- Estimating Cost of Electricity (COE) and analyzing sensitivity of key parameters impacting COE and cost of CO_2 capture based on economic updates from the updated report "Updated Costs (June 2011 Basis) for Selected Bituminous Baseline Cases [3]."

The consulting services provided by WorleyParsons also included:

- Review and evaluate capital costs for AKM24 CO_2 capture system (Appendix 4).
- Work with commercial suppliers to select appropriate heat exchangers for AKM24 system (Appendix 5).
- Work with commercial suppliers to specify commercially-feasible vacuum blowers and CO_2 compressors.

This draft of the Preliminary TEA report, revision Jan. 2015, includes updated results based on equipment cost and energy performance data provided by MAN Diesel and Turbo for vacuum blowers and CO_2 compression equipment. Comparisons are made to previous results, revision Nov. 2014, in Section 9 with previous key metrics included in the Appendix.

3. EVALUATION BASIS

The essential technical and functional requirements that are used as a basis in establishing conceptual designs for this study are provided in this section. The study methodology includes performing steady-state simulations of the various power plant technological islands with *GateCycle™* process simulation model. This model simulates the performance of the Rankine cycle portion of the plant (boiler, steam turbine, feedwater, condensate and cooling systems).

Plant performance and heat and mass balances are performed on the same basis as the Bituminous Baseline Study (BBS) that targets a net power output of 550 MWe for all cases. This design basis corresponds to 100% steam throttle flow rate, and references ambient conditions defined in the BBS. The resulting material and energy balance data from the simulation models were used to size major pieces of equipment.

3.1 Design Cases

Three cases are considered for focused study in this preliminary TEA including: Case-1A, which is an isothermal absorption-desorption system with regeneration at 0.16 bara (60°C); Case-2A, which is a temperature swing absorption-desorption system with moderate vacuum assisted regeneration at 0.40 bara (80°C); and finally Case-2B, which is a conventional absorption-desorption system with near atmospheric regeneration at 1.07 bara (105°C).

The matrix summarizing the three design cases, as well as a Case 12 re-fit from the BBS [2] is presented in Exhibit 3-1 and Exhibit 3-2.

Exhibit 3-1: Design Cases Summary

Parameter	Units	30% MEA [BBS Case 12]	AKM24, Case 1A	AKM24, Case 2A	AKM24, Case 2B
Steam Cycle	MPa/ ºC/ ºC	24.2/ 593/ 593			
	psia/ ºF/ ºF	3514.7/ 1100/ 1100			
Steam Quality at LP turbine exit (A)	%	90.8			
Condenser Pressure	mm Hg	50.8			
	in Hg	2			
Coal		Illinois No. 6	Illinois No. 6		
Boiler Efficiency	%	88	88		
Cooling water to condenser	°C °F	16 60	16 60		
Cooling water from condenser	°C °F	27 80	27 80		
Stack temperature	°C °F	57 135	32.5 - 42.1 90.6 – 107.7		
SO_2 Control		Wet Limestone Forced Oxidation	Wet Limestone Forced Oxidation		
FGD efficiency	%	98 (A)	98 (B)		
NOx Control		LNB w/OFA & SCR	LNB w/OFA & SCR		
SCR efficiency	%	86	86		
Ammonia slip (end of catalyst life)	ppmv	2	2		
Particulate Control		Fabric Filter	Fabric Filter		
Fabric Filter Efficiency	%	99.8	99.8		
Ash Distribution, Fly/Bottom	%	80/20	80/20		
Mercury removal efficiency	%	90	90		

Exhibit 3-2: CO_2 Control Summary

CO_2 Control		30% MEA	AKM24		
CO_2 Capture	%	90	90	90	90
Steam Pressure at PCC extraction	MPa	0.51	0.03	0.07	0.18
	psia	73.5	4.5	10.2	25.7
Specific Regeneration Energy	kJ/kg CO_2	3554.5	2749.7	2333.6	2111.1
	Btu/lb CO_2	1528.3	1182.2	1003.3	907.7
Specific Electric Power Requirement by CO_2 Capture System	kWh/mtCO_2	37.6	94.6	56.4	29.1
	kWh/stCO_2	34.1	85.8	51.1	26.4
Specific Cooling Load by CO_2 Capture System	kJ/kg CO_2	1020.9	770.1	691.2	627.5
	Btu/lb CO_2	438.9	331.1	297.2	269.8
SO_2 Polishing Requirement	ppmv	10	Note B	10	10
Specific Electric Power Requirement by CO_2 Compression System (A)	kWh/mtCO_2	81.9			
	kWh/stCO_2	74.3			
Specific Cooling Load by CO_2 Compression System (C)	kJ/kg CO_2	94.6	94.0	94.2	94.6
	Btu/lb CO_2	40.7	40.4	40.5	40.7

Notes:

A. Based on BBS Case 12
B. In cases with direct contact cooler (Case-2A and Case-2B), caustic soda is added to reduce SO_2 content to equivalent levels of BBS Case 12 to minimize HSS formation.
C. Specific cooling load by CO_2 compression system is estimated based on WorleyParsons process simulation.

3.2 BBS Case 12

The GateCycle™ model was calibrated using heat and material balance for NETL Case 12 detailed in the BBS report [2]. A comparison of the Case 12 performance summary in the BBS report against the performance summary derived from the WorleyParsons model is presented in Exhibit 3-3. In addition, a performance summary of the BBS Case 11 is also included.

Exhibit 3-3: Case 12 Performance Comparison

Parameter	Units	BBS Case 11	BBS Case 12	WP Model Case 12
As Received Coal Feed	lb/hr	409,528	565,820	566,210
As Received Coal Feed	kg/h	185,762	256,656	256,833
Coal Thermal Input, HHV	MMBtu/hr	4,778	6,601	6,605
Coal Thermal Input, HHV	kWth	1,400,162	1,934,519	1,935,852
Plant Gross Generation	kW	**580,400**	**662,800**	**662,830**
Coal handling	kW	440	510	510
Sorbent handling and Reagent Preparation	kW	890	1,250	1,251
Pulverizers	kW	2,780	3,850	3,853
Condensate Pump	kW	800	560	560
Miscellaneous Balance of Base Plant	kW	2,000	2,000	2,000
PA Fan	kW	1,300	1,800	1,801
FD Fan	kW	1,660	2,300	2,302
ID Fan	kW	7,050	11,120	11,128
Wet FGD	kW	2,970	4,110	4,113
SCR	kW	50	70	70
Baghouse	kW	70	100	100
CO_2 Capture System Auxiliary	kW	0	20,600	20,614
CO_2 Compression	kW	0	44,890	44,921
STG Auxiliary Load	kW	400	400	400
Circulating Water Pumps	kW	4,730	10,100	10,103
Ground Water Pumps	kW	480	910	910
Cooling Tower Fans	kW	2,440	5,230	5,231
Ash Handling	kW	530	740	741
Transformer Losses	kW	1,820	2,290	2,290
Total Aux Load	kW	**30,410**	**112,830**	**112,898**
Plant Net Generation	kW	**549,990**	**549,970**	**549,935**
Net Plant Heat Rate, HHV	Btu/kWh	8,687	12,002	12,015
Net Plant Heat Rate, HHV	kJ/kWh	9,164	12,662	12,672
Plant Net Efficiency, HHV	%	39.3	28.4	28.4
Condenser Duty	MMBtu/hr	2,178	1,646	1,646
Condenser Duty	kWth	638,309	482,395	482,532

Parameter	Units	BBS Case 11	BBS Case 12	WP Model Case 12
Flue Gas Flow	lb/hr	4,713,221	6,518,035	6,522,528
Flue Gas Flow	kg/hr	2,137,917	2,956,581	2,958,619
CO_2 Captured	lb/hr	NA	1,209,158	1,209,991
CO_2 Captured	kg/hr	N/A	548,474	548,852
Steam Extracted for CO_2 Capture System				
Flow	lb/hr	NA	1,784,175	1,785,405
Flow	kg/hr	N/A	809,302	809,860
Temperature	ºF	0	556	555
Temperature	ºC	N/A	291	291
Pressure	psia	0	74	74
Pressure	MPa	N/A	0.51	0.51

Notes:

A. ΔP, ΔT for steam from STG to PCC is not accounted, similar to the Baseline report.
B. In the BBS Report Case 11, LP turbine exhaust steam quality is approximately 76%, which is lower than what is typically recommended by ST OEM (~90%). The LP turbine steam exhaust quality of ~91% for AKM24 cases is within the recommended range and consistent with the BBS Report Case 12.

As illustrated in Exhibit 3-3, WorleyParsons' GateCycle™ model was calibrated to reproduce BBS Case 12 performance with a sufficient level of accuracy. The same model was utilized to simulate design cases of the power plant equipped with AKM-24 CO_2 capture system.

4. AKM-24 DESIGN CASES

As previously stated, three design cases were evaluated in this preliminary TEA. Process modeling was conducted using *AspenPlus® V8.4*, and capital costing was completed using *Aspen Process Economic Analyzer™ V8.4* with review by WorleyParsons. To enable accurate modeling of the AKM-24 solvent in AspenPlus® it was necessary to create a user FORTRAN kinetic subroutine that incorporated equations for solvent equilibrium CO_2 partial pressures and enzyme enhanced absorption kinetics based on laboratory data as a function of solution temperature (22 to 55°C), concentration (25% to 35% wt.), and CO_2 loading (0.3 to 0.7 mol/mol). Additionally, density and viscosity were also programmed in AspenPlus® based on similar laboratory data ranges. Modeling results have been verified against laboratory absorption data and results been presented in quarterly reports. A state point table for AKM24 is included in Exhibit 4-1.

Exhibit 4-1: State Point Table for AKM-24 Cases

	Units	Case-1A	Case-2A	Case-2B
Pure Solution		AKM-24		
Molecular Weight (Salt)	g/mol	Not Disclosed		
Normal Boiling Point (Soln.)	°C	107		
Normal Freezing Point (Soln.)	°C	-8		
Vapor Pressure @ 15°C	bar	Non-volatile salt		
Working Solution		**AKM-24**	**AKM-24**	**AKM-24**
Concentration (mass frac.)	kg/kg soln	40 wt%	35 wt%	35 wt%
Specific Gravity (15°C)	-	1.21	1.18	1.18
Specific Heat @ STP	kJ/kg-K	3.24	3.33	3.33
Viscosity @ STP	cP	6.5	4.6	4.6
Surface Tension @ STP	dyn/cm	58.4	58.4	58.4
Absorption				
Pressure	bar	1.07	1.07	1.07
Rich Exit Temperature	°C	60	44	44
Rich CO_2 Loading	mol CO_2/kg soln.	1.76	1.82	1.82
Heat of Absorption	kJ/kg CO_2	1250	1250	1250
Solution Viscosity	cP	1.64	1.55	1.55
Desorption				
Pressure	bar	0.16	0.40	1.07
Temperature	°C	60	80	107
Lean CO_2 Loading	mol CO_2/kg soln.	1.08	0.96	0.96
Heat of Desorption	kJ/kg CO_2	1250	1250	1250

Details of the cases examined in this Preliminary TEA are as follows:

Case-1A: 550 MWe supercritical pulverized coal-fired (SCPC) power plant equipped with 40% AKM24 (w/w) in an isothermal absorption-desorption CO_2 capture system with vacuum-assisted regeneration (0.16 bara, 60°C). Case-1A PFD for the CO_2 unit is presented in Exhibit 4-2 and the heat and material balance (HMB) is presented in Exhibit 4-5. A higher concentration of solvent is enabled for this case due to less risk of precipitation since a lower solvent rich loading is achieved in the absorption process.

Case-2A:- 550 MWe SCPC power plant equipped with 35% AKM24 in an absorption-desorption CO_2 capture system with moderate vacuum-assisted regeneration (0.40 bara, 80°C). Case-2A PFD for the CO_2 unit is presented in Exhibit 4-3 and the HMB is presented in Exhibit 4-6.

Case-2B:- 550 MWe SCPC power plant equipped with 35% AKM24 in an absorption-desorption CO_2 capture system with near atmospheric regeneration (1.07 bara, 105°C). Case-2B PFD for the CO_2 unit is presented in Exhibit 4-4 and the HMB is presented in Exhibit 4-7.

While PFDs and HMBs for the CO_2 unit are presented herein, HMBs for the power plant are presented in Appendix 1. The power plant HMBs in Appendix 1 are based upon the Nov. 2014 revision of the Preliminary TEA and require updated calculations but are generally informative to understand the basic layout of the plant. It is also worth noting that the difference in power plant size between the Jan. 2015 revision presented here and the previous Nov. 2014 revision is generally less than 2.5%. Updated HMBs will be included with the Final TEA. Similarly, major equipment lists for the Nov. 2014 revision of the SCPC power plant are included in Appendix 2. These will also be updated in the Final TEA.

Unique to the systems designed by Akermin is the implementation of a proprietary immobilized biocatalyst to accelerate the rate of absorption and rate of desorption in the absorber and stripper, respectively. Akermin has evaluated a broad range of carbonic anhydrases from various suppliers and evaluated them for suitability for immobilization (sufficient purity), high activity in the target solvent (AKM-24); stability at high pH, thermal stability suitable for long term bench unit demonstration at 40°C, and availability on a multi-kilogram scale to support development and demonstration activities. Akermin selected carbonic anhydrase from Novozymes A/S Denmark as the most suitable enzyme for development and established a supply arrangement with the company.

In addition, Akermin is developing an optimal method to immobilize carbonic anhydrase on micro-particles. This micro-particle technology builds upon previous work by Akermin where several approaches to immobilize carbonic anhydrase on random and structured packing were investigated. Akermin down-selected the best performing immobilization strategy and deployed the biocatalyst as a coating packing in the laboratory that demonstrated as much as 17-fold enhancement of CO_2 capture mass transfer coefficients relative to room temperature blank potassium carbonate, and 10-fold enhancement at 45°C relative to blank potassium carbonate. The formulation was scaled-up and coated on 275 Liters of M500X structured packing and installed in a bench unit system that was designed and tested under project DE-FE0004228. This unit operated for over 2800 hours on flue gas with minimal observed decline in activity.

The power plant details for this study are identical to the NETL Case 12, which assumes a supercritical pulverized coal power plant with 15.9% CO_2. Additional details available in the BBS report [2].

Exhibits below present the basic process flow diagrams for each of the Akermin cases. A general process description follows for all cases and also noting the specific differences in the configurations.

Exhibit 4-2: Case-1A Process Flow Diagram

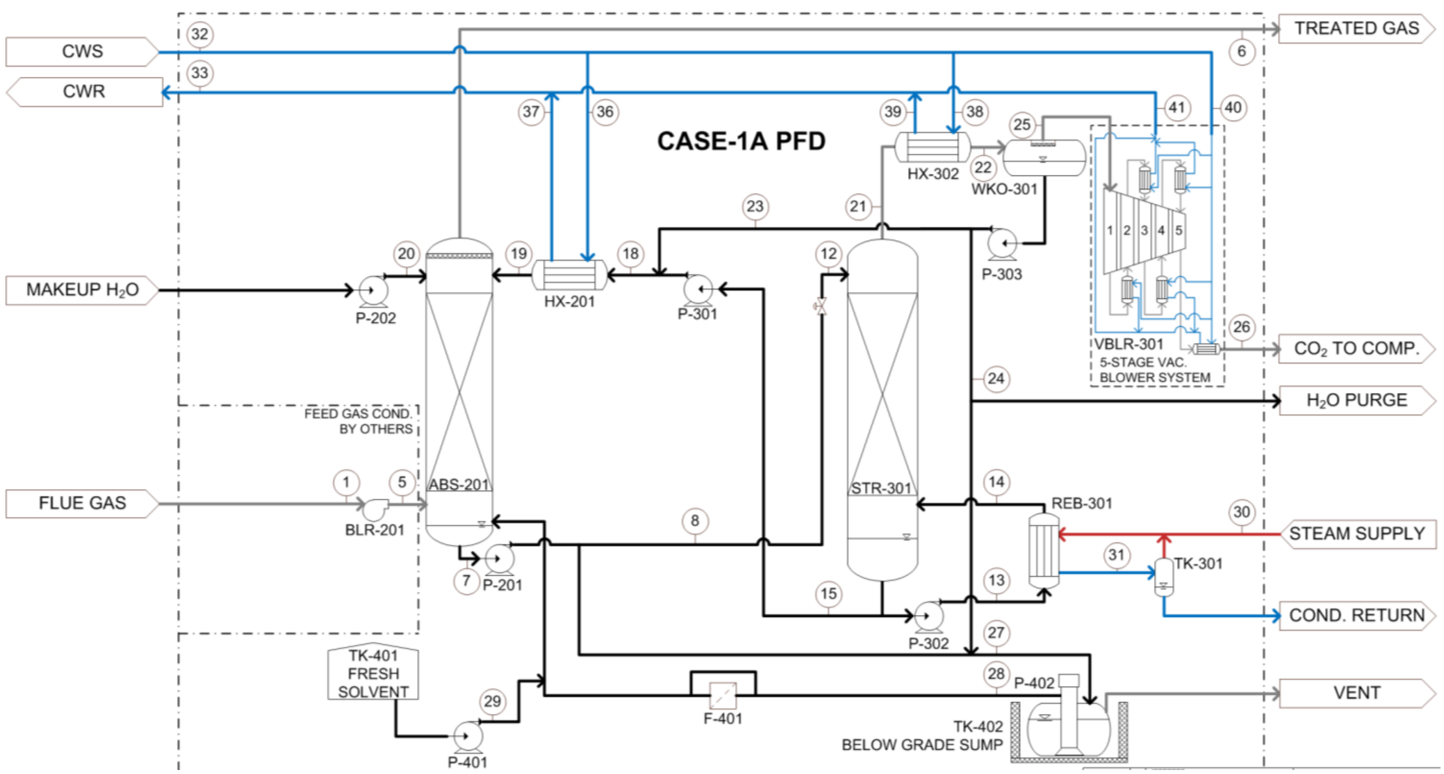


Exhibit 4-3: Case-2A Process Flow Diagram

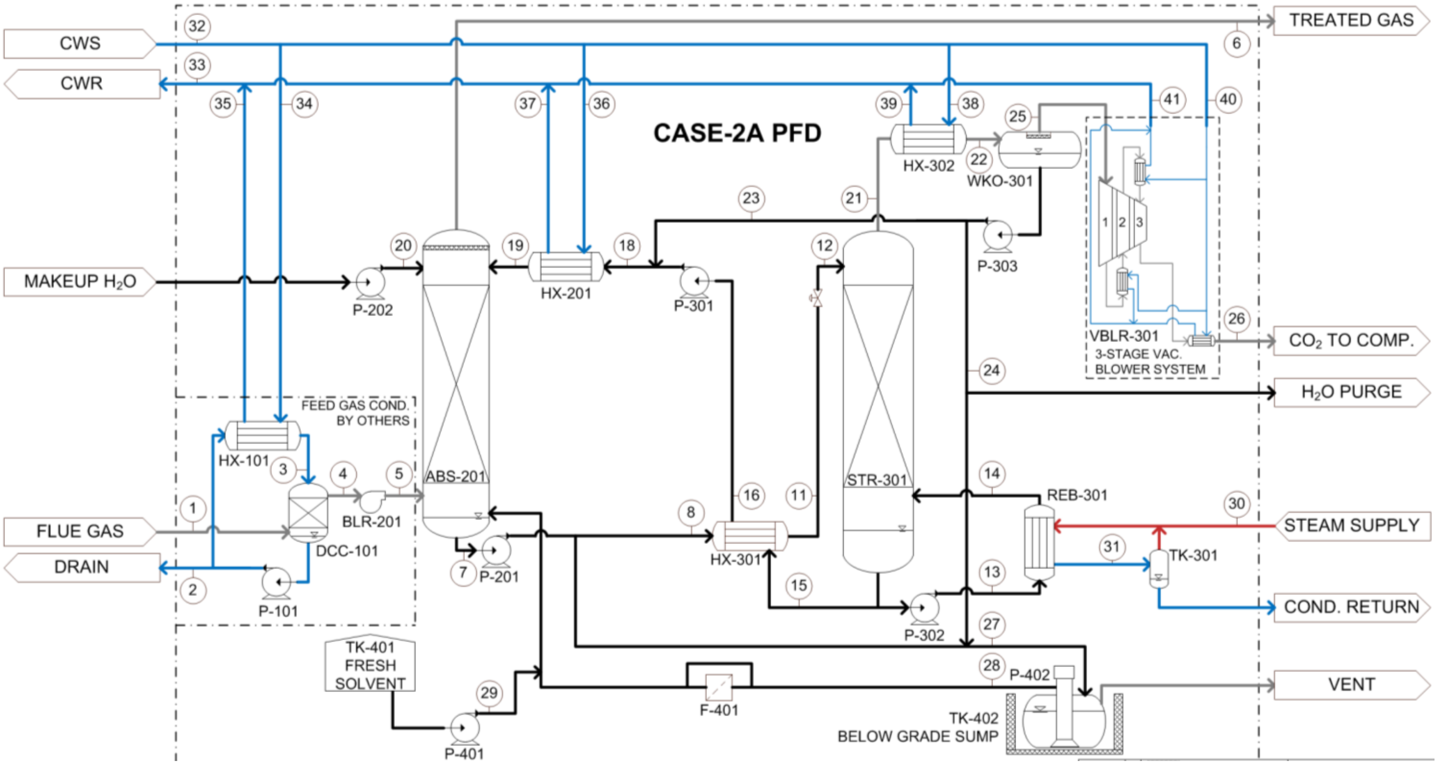
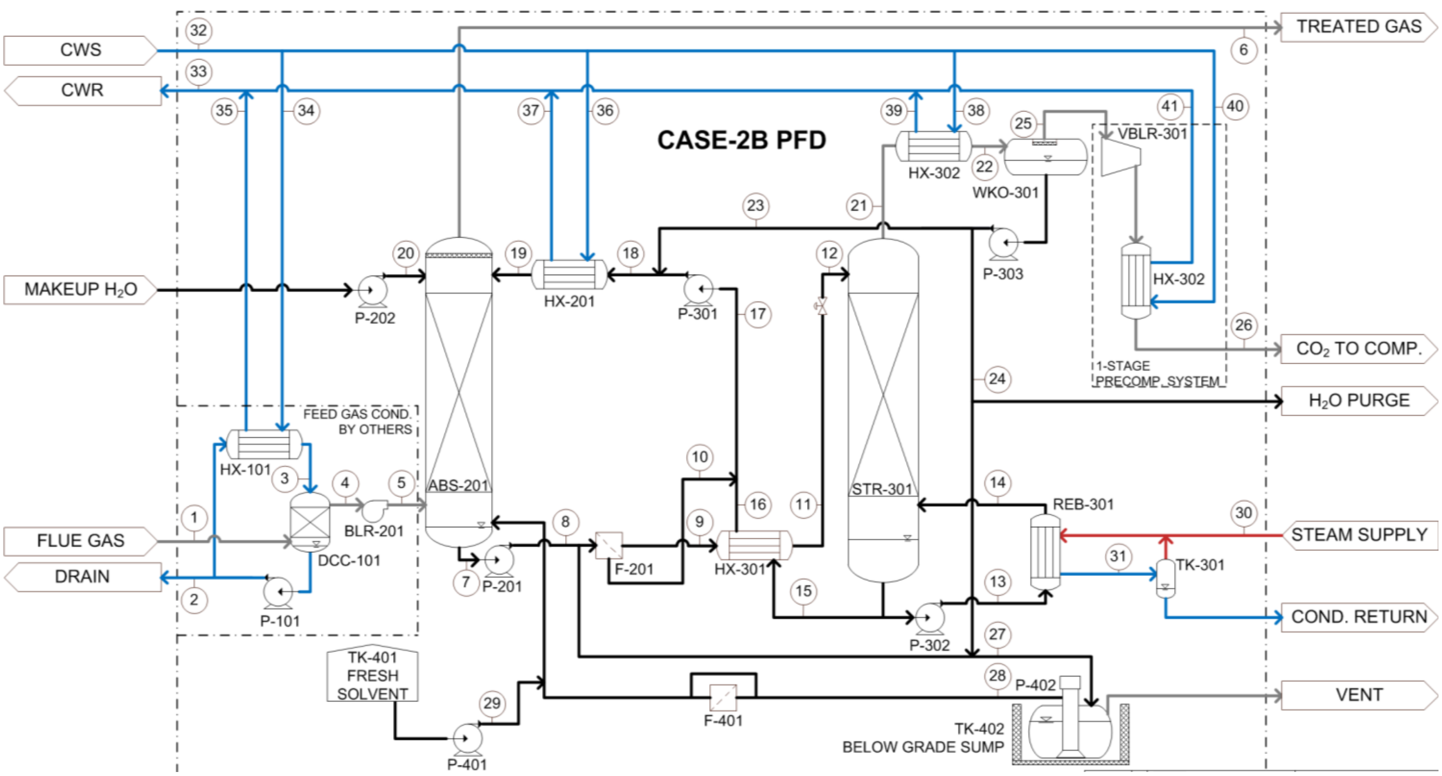


Exhibit 4-4: Case-2B Process Flow Diagram



Flue gas from a super critical pulverized coal (SCPC) boiler after passing through a Baghouse to remove ash, dust and mercury, a flue gas desulfurization unit (FGD) unit to reduce concentrations of sulfur oxide compounds (SO_x) is received at 58°C on the technical boundary limit (TBL) of the CO_2 removal system, process point (1) . With the exception of Case-1A that has no direct contact cooler (DCC), flue gas enters the bottom of DCC-101 where the temperature of the gas is adjusted to about 35°C, which is optimal for CO_2 capture in Cases-2A and 2B. Caustic soda may also be used in the direct contact cooler to further minimize SO_x concentrations in Cases 2A and 2B. A water circulation loop exits the bottom of DCC-101 and is delivered via a centrifugal pump, P-101, where excess condensate (produced water) is removed at (2) while the desired pump-around fraction enters the tube-side of a trim cooler, HX-101 and then returned to the top of DCC-101 at (3).

Preconditioned flue gas exits the top of DCC-101 at (4) and is pulled through an induced draft fan, BLR-201; which provides pressure boost to achieve about 7 kpag absorber bottom pressure, sufficient to overcome pressure drops in the column. Next, the flue gas enters the bottom of the absorber, ABS-201, at (5) where 90% of the CO_2 is removed from the gas by chemical absorption into a counter-current circulating aqueous non-volatile salt solution (sometimes referred to as a solvent in this document). The 'solvent' is initially lean in CO_2 and augmented with Akermin's biocatalyst particles when entering the top of ABS-201 at (19). The biocatalyst serves to enhance the liquid film mass transfer coefficient, which results in improved overall mass transfer rates. The treated gas exits the top of ABS-201 at (6) and exits the TBL of the CO_2 capture unit.

The solvent rich in CO_2 exits the bottom of ABS-201 at (7) and is pumped via a centrifugal pump, P-201, to a number of unit operations depending on the specific case:

- In Case-1A the rich solvent continues from (8) through a control valve to point (12) where the rich solvent enters the top of the regeneration unit, STR-301. No cross-exchanger is included in this case since the rich-lean approach temperature is quite similar.
- In Case-2A the rich solvent continues through (8) to the tube-side of a heat-recovery cross-exchanger, HX-301, where heat from the hot regenerated lean solvent stream at (15) is transferred to the rich solvent stream. The pre-heated rich solvent exits HX-301 at (11) and continues to a flash valve where pressure is dropped at (12), and the rich solvent enters the top of the regeneration unit, STR-301.
- In Case-2B the rich solvent continues through (8) to a biocatalyst recovery system, F-201, where virtually all biocatalyst particles are removed from the rich solvent stream and recycled to the lean solvent at (10). Since the particles are wet, they will carry some rich solution to the lean stream, but this been accounted for in the heat and mass balance with an estimated 9.3% rich solution recycled with the biocatalyst slurry. The clarified rich solvent continues through (9) to the tube-side of a cross-exchanger, HX-301, where heat

is recovered from the lean solvent stream at (15). The pre-heated rich solvent exits HX-301 at (11) and continues through a back-pressure valve to top of STR-301.

The rich solvent entering the top of STR-301 at (12) flows down the regenerator where CO_2 is released from the solvent via steam stripping. The lean solvent exiting the bottom of STR-301 is split pumped via a centrifugal pump, P-302, through (13) into the tube-side of a heat exchanger, REB-301. Steam extracted from the turbine outside the TBL pressure steam entering the shell-side of REB-301 at (30) condenses, exiting REB-301 at (31) and settling into a condensate pot, TK-301, before exiting the TBL of the system. The latent heat transferred to the lean solvent generates stripping steam mixed with the solvent exiting REB-301 at (14) where it reenters the bottom of STR-301. The stripping steam rises in the column to purge CO_2 while the solvent again falls to the bottom of STR-301.

The lean solvent not pumped to REB-301 flows through (15) where, in Case-2A and Case-2B, it enters the shell-side of HX-301 and preheats the cold, rich solvent. The cooled lean solvent exits HX-301 at (16), and, in Case-2B, mixes with the recovered biocatalyst particles from F-201 (which represents the biocatalyst recovery system).

The lean solvent flows through (17) to a centrifugal pump, P-301, where the lean solution is pumped uphill and mixes with condensate from the regenerator overhead condenser, HX-302. The solvent then flows through (18) and enters the tube side of a trim cooler, HX-201, where temperature is adjusted for optimal CO_2 absorption. The lean solvent exits HX-201 at (19) and enters ABS-201 to begin the CO_2 absorption process anew. Any makeup water required in the process enters the TBL and is pumped via a centrifugal pump, P-202, through (20) into the top of ABS-201.

Released CO_2 mixed with water vapor exits the top of STR-301 at (21) and enters the tube side of the stripper overhead condenser, HX-302. The cooled CO_2 mixed with liquid and vapor water in (22) enters a water knock-out, WKO-301, where condensate is pumped from the bottom of WKO-301 via a centrifugal pump, P-303, and is either returned to the system through (23) or purged from the system through (24). Saturated CO_2 is pulled from the top of WKO-301 through (25) into either a vacuum blower system (Case-1A, Case-2A) or a pre-compression system (Case-2B), VBLR-301. From VBLR-301 the CO_2 stream flows through (26) outside the TBL for further compression, dehydration, and injection.

Cooling water from the cooling tower enters the TBL at (32) and is distributed as required to the shell-side of HX-101, HX-201, HX-302, and VBLR-301 through lines (34), (36), (38), and (40), respectively. Cooling water return from HX-101, HX-201, HX-302, and VBLR-301, from lines (35), (37), (39), and (41), respectively, mixes and is returned through (33) to the cooling tower beyond the TBL.

Heat and mass balance schematics are presented in Exhibit 4-5, Exhibit 4-6, and Exhibit 4-7.

Exhibit 4-5: Case-1A CO_2 Unit HMB

Stream Table	Stream:	1	5	6	7	8	12	13	14	15	18	19	20	21	22
Temperature	°C	58.0	63.1	42.1	60.1	60.2	60.3	60.1	60.1	60.1	59.5	41.6	16.0	49.2	22.0
Pressure	bara	1.00	1.05	1.03	1.05	5.88	1.06	0.23	0.21	0.16	2.50	2.48	3.50	0.14	0.12
Standard Gas Flow [Wet]	Nm3/h*10-6	2.195	2.195	1.700										0.790	
Liquid Volume Flow	LPM				215176	215189		210065		210065	213747	211464	0		
Component Mole Fractions:															
Water	mol-%	15.4%	15.4%	6.5%	80.8%	80.8%	80.8%	82.1%	82.1%	82.1%	82.6%	82.6%	100.0%	66.2%	66.2%
Potassium Ion	mol-%	0.0%	0.0%	0.0%	7.1%	7.1%	7.1%	7.4%	7.4%	7.4%	7.3%	7.3%	0.0%	0.0%	0.0%
AKM-24	mol-%	0.0%	0.0%	0.0%	2.3%	2.3%	2.3%	4.5%	4.5%	4.5%	4.4%	4.4%	0.0%	0.0%	0.0%
Biocarbonate Ion	mol-%	0.0%	0.0%	0.0%	4.9%	4.9%	4.9%	3.0%	3.0%	3.0%	2.9%	2.9%	0.0%	0.0%	0.0%
AKM-24H	mol-%	0.0%	0.0%	0.0%	4.9%	4.9%	4.9%	3.0%	3.0%	3.0%	2.9%	2.9%	0.0%	0.0%	0.0%
Carbon Dioxide	mol-%	13.5%	13.5%	1.7%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	33.8%	33.8%
Nitrogen	mol-%	67.9%	67.9%	87.7%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Oxygen	mol-%	2.4%	2.4%	3.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Argon	mol-%	0.8%	0.8%	1.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Component Mass Fractions:															
Water	wt-%	9.6%	9.6%	4.2%	52.6%	52.6%	52.6%	54.5%	54.5%	54.5%	55.2%	55.2%	100.0%	44.5%	44.5%
Potassium Ion	wt-%	0.0%	0.0%	0.0%	10.1%	10.1%	10.1%	10.7%	10.7%	10.7%	10.5%	10.5%	0.0%	0.0%	0.0%
AKM-24	wt-%	0.0%	0.0%	0.0%	8.4%	8.4%	8.4%	16.8%	16.8%	16.8%	16.5%	16.5%	0.0%	0.0%	0.0%
Biocarbonate Ion	wt-%	0.0%	0.0%	0.0%	10.7%	10.7%	10.7%	6.7%	6.7%	6.7%	6.6%	6.6%	0.0%	0.0%	0.0%
AKM-24H	wt-%	0.0%	0.0%	0.0%	18.2%	18.1%	18.1%	11.3%	11.3%	11.3%	11.1%	11.1%	0.0%	0.0%	0.0%
Carbon Dioxide	wt-%	20.6%	20.6%	2.7%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	55.4%	55.4%
Nitrogen	wt-%	66.0%	66.0%	88.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Oxygen	wt-%	2.6%	2.6%	3.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Argon	wt-%	1.1%	1.1%	1.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Total Mole Flow	kmol/s	25.8	25.8	20.0	155	155	155	149	149	149	153	153	0.0	9.28	9.28
Total Mass Flow	kg/s	743	743	557	4299	4299	4299	4050	4050	4050	4113	4113	0	249	249
Vapor Fraction		100.00%	100.00%	100.00%	0.00%	0.00%	0.00%	0.00%	3.95%	0.00%	0.00%	0.00%	0.00%	100.00%	43.37%
Liquid Fraction		0.00%	0.00%	0.00%	100.00%	100.00%	100.00%	100.00%	96.05%	100.00%	100.00%	100.00%	100.00%	0.00%	56.63%
Mass Density	kg/m3	1.05	1.08	1.10	1199	1199	1193.7	1157		1157	1155	1167	998	0.140	0.302
Average Molecular Weight	kg/kmol	28.83	28.83	27.89	27.67	27.67	27.67	27.15	27.15	27.15	26.94	26.94	18.02	26.79	26.79
Mixture Critical Pressure	bara	68.5	68.5	47.3	184.9	184.9	184.9	187.5	187.5	187.5	188.2	188.2	220.5	171.0	171.0
Mixture Critical Temperature	°C	-41.9	-41.9	-109.1	349.6	349.6	349.6	351.5	351.5	351.5	352.0	352.0	374.1	258.3	258.3
Mixture Heat Capacity	kJ/kg-K	1.08	1.08	1.06	2.99	2.99		3.26		3.26	3.27	3.24	4.18	1.32	
Mixture CpCv Ratio		1.37	1.37	1.39	1.21	1.21	1.21	1.00		1.00	1.15	1.09	1.01	1.31	1.07
Mass Enthalpy	MJ/kg	-3.10	-3.09	-0.79	-8.85	-8.85	-8.85	-8.63	-8.54	-8.63	-8.74	-8.80	-15.91	-10.91	-11.88
Compressibility Factor		0.9986	0.9986	0.9993			0.9973							0.9989	0.9992
Vapor Standard Volume	m3/kmol	27.5	26.6	25.4										191.2	
Vapor Thermal Conductivity	mW/m-K	25.2	25.6	25.9			22.4							19.7	16.7
Mixture Liquid Viscosity	cP				1.17	1.16	1.16	1.20		1.20	1.17	1.64	1.07		0.80
Liquid Standard Volume	L/kmol				23.1	23.1		23.5		23.5	23.3	23.1	18.0		
Liquid Surface Tension	mN/m				69.6	69.6	69.6	66.2		70.6	70.7	73.8	73.3		73.3
Liquid Thermal Conductivity	mW/m-K				1088	1090	1089	2012		2012	1988	2071	594		600
CO2 Capture	%	0.0%	0.0%	90.0%											
AKM-24 Concentration	wt.%				39.5%	39.5%	39.5%	40.6%	40.6%	40.6%	40.0%	40.0%			
CO2 Loading	mol/mol				0.682	0.681	0.681	0.400	0.400	0.400	0.400	0.400			

Stream Table	Stream:	23	24	25	26	27	28	29	30	31	32	33	36	37	38
Temperature	°C	20.8	20.8	20.8	21.9	--	--	--	70.1	70.1	16.0	27.0	16.0	27.0	16.0
Pressure	bara	2.50	2.50	0.11	0.83	--	--	--	0.31	0.30	5.00	4.98	5.00	4.98	5.00
Standard Gas Flow [Wet]	Nm3/h*10-6			0.344	0.275				0.764						
Liquid Volume Flow	LPM	3759	1917			0	0	0		9898	715735	717007	313441	313998	315131
Component Mole Fractions:															
Water	mol-%	100.0%	100.0%	22.5%	3.2%	0.0%	0.0%	0.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Potassium Ion	mol-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
AKM-24	mol-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Biocarbonate Ion	mol-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
AKM-24H	mol-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Carbon Dioxide	mol-%	0.0%	0.0%	77.5%	96.8%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Nitrogen	mol-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Oxygen	mol-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Argon	mol-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Component Mass Fractions:															
Water	wt-%	100.0%	100.0%	10.6%	1.3%	0.0%	0.0%	0.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Potassium Ion	wt-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
AKM-24	wt-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Biocarbonate Ion	wt-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
AKM-24H	wt-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Carbon Dioxide	wt-%	0.0%	0.0%	89.4%	98.7%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Nitrogen	wt-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Oxygen	wt-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Argon	wt-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Total Mole Flow	kmol/s	3.47	1.77	4.04	3.24	0.00	0.00	0.00	8.97	8.97	661	661	290	290	291
Total Mass Flow	kg/s	63	32	154	140	0	0	0	162	162	11910	11910	5216	5216	5244
Vapor Fraction		0.00%	0.00%	100.00%	100.00%				100.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Liquid Fraction		100.00%	100.00%	0.00%	0.00%				0.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
Mass Density	kg/m3	998.194	998.194	0.172	1.47				0.200	980	998	997	998	997	998
Average Molecular Weight	kg/kmol	18.02	18.02	38.17	43.17				18.02	18.02	18.02	18.02	18.02	18.02	18.02
Mixture Critical Pressure	bara	220.5	220.5	106.7	78.5				220.5	220.5	220.5	220.5	220.5	220.5	220.5
Mixture Critical Temperature	°C	374.1	374.1	108.1	42.0				374.1	374.1	374.1	374.1	374.1	374.1	374.1
Mixture Heat Capacity	kJ/kg-K	4.18	4.18	0.95	0.86				1.88	4.17	4.18	4.17	4.18	4.17	4.18
Mixture CpCv Ratio		1.01	1.01	1.30	1.30					1.01	1.01	1.01	1.01	1.01	1.01
Mass Enthalpy	MJ/kg	-15.89	-15.89	-9.43	-9.01				-13.35	-15.69	-15.91	-15.87	-15.91	-15.87	-15.91
Compressibility Factor				0.9993	0.9956										
Vapor Standard Volume	m3/kmol			222.0	29.4				90.2						
Vapor Thermal Conductivity	mW/m-K			16.6	16.3										
Mixture Liquid Viscosity	cP	0.82	0.82							0.34	1.07	0.80	1.07	0.80	1.07
Liquid Standard Volume	L/kmol	18.0	18.0							18.4	18.0	18.1	18.0	18.1	18.0
Liquid Surface Tension	mN/m	73.5	73.5							64.4	73.3	71.6	73.3	71.6	73.3
Liquid Thermal Conductivity	mW/m-K	598	598							664	594	612	594	612	594
CO2 Capture	%														
AKM-24 Concentration	wt.%														
CO2 Loading	mol/mol														

Stream Table	Stream:	39	40	41
Temperature	°C	27.0	16.0	27.0
Pressure	bara	4.98	5.00	4.98
Standard Gas Flow [Wet]	Nm3/h*10-6			
Liquid Volume Flow	LPM	315691	87163	87318
Component Mole Fractions:				
Water	mol-%	100.0%	100.0%	100.0%
Potassium Ion	mol-%	0.0%	0.0%	0.0%
AKM-24	mol-%	0.0%	0.0%	0.0%
Biocarbonate Ion	mol-%	0.0%	0.0%	0.0%
AKM-24H	mol-%	0.0%	0.0%	0.0%
Carbon Dioxide	mol-%	0.0%	0.0%	0.0%
Nitrogen	mol-%	0.0%	0.0%	0.0%
Oxygen	mol-%	0.0%	0.0%	0.0%
Argon	mol-%	0.0%	0.0%	0.0%
Component Mass Fractions:				
Water	wt-%	100.0%	100.0%	100.0%
Potassium Ion	wt-%	0.0%	0.0%	0.0%
AKM-24	wt-%	0.0%	0.0%	0.0%
Biocarbonate Ion	wt-%	0.0%	0.0%	0.0%
AKM-24H	wt-%	0.0%	0.0%	0.0%
Carbon Dioxide	wt-%	0.0%	0.0%	0.0%
Nitrogen	wt-%	0.0%	0.0%	0.0%
Oxygen	wt-%	0.0%	0.0%	0.0%
Argon	wt-%	0.0%	0.0%	0.0%
Total Mole Flow	kmol/s	291	80.5	80.5
Total Mass Flow	kg/s	5244	1450	1450
Vapor Fraction		0.00%	0.00%	0.00%
Liquid Fraction		100.00%	100.00%	100.00%
Mass Density	kg/m3	997	998	997
Average Molecular Weight	kg/kmol	18.02	18.02	18.02
Mixture Critical Pressure	bara	220.5	220.5	220.5
Mixture Critical Temperature	°C	374.1	374.1	374.1
Mixture Heat Capacity	kJ/kg-K	4.17	4.18	4.17
Mixture CpCv Ratio		1.01	1.01	1.01
Mass Enthalpy	MJ/kg	-15.87	-15.91	-15.87
Compressibility Factor				
Vapor Standard Volume	m3/kmol			
Vapor Thermal Conductivity	mW/m-K			
Mixture Liquid Viscosity	cP	0.80	1.07	0.80
Liquid Standard Volume	L/kmol	18.1	18.0	18.1
Liquid Surface Tension	mN/m	71.6	73.3	71.6
Liquid Thermal Conductivity	mW/m-K	612	594	612
CO2 Capture	%			
AKM-24 Concentration	wt.%			
CO2 Loading	mol/mol			

Blowers:		BLR-201	VBLR-301
Number of Stages	--	1	16
Inlet Mass Flow Rate	kg/hr	2675730	555174
Inlet Temperature	C	58.0	20.8
Comp. Ratio Per Stage	--	1.05	1.14
Cp/Cv Ratio		1.30	1.30
Average Molecular Weight		28.83	38.17
Isentropic Efficiency		85%	--
Brake Power	kW	4098	31191
Electric Power Efficiency	%	95.0%	97.0%
Electric Power	kWe	4314	32156
Specific Duty	kWh/tCO2	**8.7**	**64.8**

Columns:		ABS-201	STR-301
Packing Diameter	m	23.8	23.5
Packing Height	m	26.5	20.6
Packing Volume	m3	11794	8913
Packing Type	--	M350Y	M350Y
Area Efficiency		0.50	0.50

Pumps:		Total	P-201	P-202	P-301	P-302	P-303	P-401	P-402
Description	--	--	Rich Pump	H2O Mkup	Lean Pump	Reb. Pump	Cond. Pump	Solv. Mkup.	Sump Pump
Mass Flow Rate	kg/hr	--	15476500	0	14581400	14581400	339936	1547650	1547650
Density	kg/m3	--	1199	998	1157	1157	998	1199	1199
Pressure Boost	bara	--	4.83	2.50	4.83	0.07	2.39	4.83	4.83
Pump Efficiency	%	--	75%	75%	75%	75%	75%	75%	75%
Brake Power	kW	5085	2308	0	2253	32.2	30.1	230.8	230.8
Electric Power Efficiency	%	95.0%	95.0%	95.0%	95.0%	95.0%	95.0%	95.0%	95.0%
Electric Power	kWe	5352	2429	0	2372	33.9	31.7	242.9	242.9
Specific Duty	kWh/tCO2	**10.78**	**4.89**	**0.00**	**4.78**	**0.07**	**0.06**	**0.49**	**0.49**

Exchangers		HX-201	HX-302	HX-303	REB-301
Description	--	Trim Cooler	OH Cond.	VBLR Clr.	Reboiler
Cold Side		CW	CW	CW	AKM-24
Hot Side		AKM-24	Wet CO2	Wet CO2	LP Steam
Cold Inlet Temperature	°C	16.0	16.0	16.0	60.1
Cold Outlet Temperature	°C	27.0	27.0	27.0	60.1
Hot Inlet Temperature	°C	59.5	49.2	217.0	70.1
Hot Outlet Temperature	°C	41.6	22.0	22.0	70.1
Cold Side Temp. Delta	°C	25.6	6.00	6.00	10.0
Hot Side Temp. Delta	°C	32.5	22.2	190.0	10.0
Log Mean Temp. Delta	°C	28.9	12.4	53.2	10.0
Heat Exchanger Duty	MWth	**-239.4**	**-240.7**	**-66.6**	**377.1**
UA Factor	MW/K	8.3	19.5	1.251	37.7
Exchanger Specific Duty	GJ/tCO2	**-1.74**	**-1.747**	**-0.4831**	**2.74**

Reboiler:		
CO2 Absorbed	t/hr	496.3
CO2 Released	t/hr	496.3
Reboiler Duty	MW	377.1
Specific Reboiler Duty	GJ/tCO2	2.74
Reboiler Temp.	°C	60.1
Steam-to-Power Efficiency	%	8.13%
Equivalent Work	kWh/tCO2	**61.7**

Equivalent Work		
Blowers	kWh/tCO2	8.7
Circulation Pumps	kWh/tCO2	10.8
Reboiler	kWh/tCO2	61.7
Vacuum Blower	kWh/tCO2	64.8
Compressor	kWh/tCO2	119.2
Total Equivalent Work	kWh/tCO2	**265.2**

Exhibit 4-6: Case-2A CO_2 Unit HMB

Stream Table	Stream:	1	2	3	4	5	6	7	8	11	12	13	14	15	16
Temperature	°C	58.0	54.3	35.0	35.0	41.8	32.6	44.3	44.4	74.9	69.9	79.9	79.9	79.9	50.7
Pressure	bara	1.00	1.00	1.20	0.98	1.05	1.03	1.05	5.88	5.88	1.06	0.46	0.44	0.40	0.40
Standard Gas Flow [Wet]	Nm3/h*10-6	2.125			1.908	1.908	1.605								
Liquid Volume Flow	LPM		2789	73570				166341	166325	170295		168497		168497	165225
Component Mole Fractions:															
Water	mol-%	15.4%	100.0%	100.0%	5.8%	5.8%	4.0%	83.2%	83.2%	83.2%	83.3%	85.2%	85.2%	85.2%	85.2%
Potassium Ion	mol-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	6.0%	6.0%	6.0%	6.0%	6.2%	6.2%	6.2%	6.2%
AKM-24	mol-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	1.2%	1.2%	1.3%	2.0%	3.7%	3.7%	3.7%	3.7%
Biocarbonate Ion	mol-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	4.8%	4.8%	4.8%	4.0%	2.5%	2.5%	2.5%	2.5%
AKM-24H	mol-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	4.8%	4.8%	4.8%	4.0%	2.5%	2.5%	2.5%	2.5%
Carbon Dioxide	mol-%	13.5%	0.0%	0.0%	15.0%	15.0%	1.8%	0.0%	0.0%	0.1%	0.8%	0.0%	0.0%	0.0%	0.0%
Nitrogen	mol-%	67.9%	0.0%	0.0%	75.6%	75.6%	90.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Oxygen	mol-%	2.4%	0.0%	0.0%	2.7%	2.7%	3.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Argon	mol-%	0.8%	0.0%	0.0%	0.9%	0.9%	1.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Component Mass Fractions:															
Water	wt-%	9.6%	100.0%	100.0%	3.5%	3.5%	2.6%	56.6%	56.6%	56.7%	57.2%	60.0%	60.0%	60.0%	60.0%
Potassium Ion	wt-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	8.9%	8.9%	8.9%	8.9%	9.4%	9.4%	9.4%	9.4%
AKM-24	wt-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	4.6%	4.6%	4.8%	7.7%	14.8%	14.8%	14.8%	14.8%
Biocarbonate Ion	wt-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	11.1%	11.1%	11.0%	9.3%	5.9%	5.9%	5.9%	5.9%
AKM-24H	wt-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	18.8%	18.8%	18.6%	15.7%	9.9%	9.9%	9.9%	9.9%
Carbon Dioxide	wt-%	20.6%	0.0%	0.0%	22.0%	22.0%	2.8%	0.0%	0.0%	0.1%	1.3%	0.0%	0.0%	0.0%	0.0%
Nitrogen	wt-%	66.0%	0.0%	0.0%	70.5%	70.5%	89.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Oxygen	wt-%	2.6%	0.0%	0.0%	2.8%	2.8%	3.6%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Argon	wt-%	1.1%	0.0%	0.0%	1.2%	1.2%	1.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Total Mole Flow	kmol/s	25.0	2.54	67.7	22.4	22.4	18.9	126	126	126	127	123	123	123	123
Total Mass Flow	kg/s	720	45.8	1220	674	674	531	3333	3333	3333	3333	3141	3141	3141	3141
Vapor Fraction		100.00%	0.00%	0.00%	100.00%	100.00%	100.00%	0.00%	0.00%	0.00%	1.01%	0.00%	4.30%	0.00%	0.00%
Liquid Fraction		0.00%	100.00%	100.00%	0.00%	0.00%	0.00%	100.00%	100.00%	100.00%	98.99%	100.00%	95.70%	100.00%	100.00%
Mass Density	kg/m3	1.05	986	995	1.15	1.21	1.14	1202	1202	1174	89.6	1119		1119	1141
Average Molecular Weight	kg/kmol	28.83	18.02	18.02	30.05	30.05	28.15	26.46	26.46	26.45	26.25	25.59	25.59	25.59	25.59
Mixture Critical Pressure	bara	68.5	220.5	220.4	51.3	51.3	42.9	189.2	189.2	189.2	189.8	193.1	193.1	193.1	193.1
Mixture Critical Temperature	°C	-41.9	374.1	374.1	-89.1	-89.1	-121.6	352.5	352.5	352.4	351.1	355.4	355.4	355.4	355.4
Mixture Heat Capacity	kJ/kg-K	1.08	4.18	4.17	1.02	1.02	1.05	2.98	2.98	3.06		3.40		3.40	3.35
Mixture CpCv Ratio		1.37	1.04	1.01	1.38	1.37	1.40	1.13	1.13	1.26	1.21	1.00		1.00	1.10
Mass Enthalpy	MJ/kg	-3.10	-15.75	-15.83	-2.42	-2.42	-0.59	-9.65	-9.65	-9.56	-9.56	-9.42	-9.32	-9.42	-9.52
Compressibility Factor		0.9986			0.9989	0.9989	0.9993				0.9953				
Vapor Standard Volume	m3/kmol	27.5			26.1	24.9	24.7								
Vapor Thermal Conductivity	mW/m-K	25.2			24.0	24.5	25.4				20.7				
Mixture Liquid Viscosity	cP		0.48	0.67				1.49	1.49	0.85	0.80	0.69		0.69	1.12
Liquid Standard Volume	L/kmol		18.3	18.1				22.0	22.0	22.5		22.9		22.9	22.4
Liquid Surface Tension	mN/m		67.0	70.4				71.8	71.7	66.4	67.6	62.7		66.6	71.7
Liquid Thermal Conductivity	mW/m-K		639	624				709	709	674	1005	1717		1717	1843
CO2 Capture	%	0.0%	0.0%		0.0%	0.0%	90.0%								
AKM-24 Concentration	wt.%							34.9%	34.9%	34.9%	34.9%	35.6%	35.6%	35.6%	35.6%
CO2 Loading	mol/mol							0.800	0.800	0.792	0.669	0.400	0.400	0.400	0.400

Stream Table	Stream:	18	19	20	21	22	23	24	25	26	27	28	29	30	31
Temperature	°C	50.2	32.0	16.0	63.7	22.0	21.7	21.7	21.7	22.0	--	--	--	89.9	89.9
Pressure	bara	2.50	2.48	3.50	0.38	0.36	2.50	2.50	0.35	2.67	--	--	--	0.70	0.69
Standard Gas Flow [Wet]	Nm3/h*10-6				0.533				0.279	0.261				0.646	
Liquid Volume Flow	LPM	168097	166547	0			2917	310			0	0	0		8494
Component Mole Fractions:															
Water	mol-%	85.5%	85.5%	100.0%	51.5%	51.5%	100.0%	100.0%	7.6%	1.0%	0.0%	0.0%	0.0%	100.0%	100.0%
Potassium Ion	mol-%	6.0%	6.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
AKM-24	mol-%	3.6%	3.6%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Biocarbonate Ion	mol-%	2.4%	2.4%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
AKM-24H	mol-%	2.4%	2.4%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Carbon Dioxide	mol-%	0.0%	0.0%	0.0%	48.5%	48.5%	0.0%	0.0%	92.4%	99.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Nitrogen	mol-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Oxygen	mol-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Argon	mol-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Component Mass Fractions:															
Water	wt-%	60.6%	60.6%	100.0%	30.3%	30.3%	99.9%	99.9%	3.3%	0.4%	0.0%	0.0%	0.0%	100.0%	100.0%
Potassium Ion	wt-%	9.3%	9.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
AKM-24	wt-%	14.6%	14.6%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Biocarbonate Ion	wt-%	5.8%	5.8%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
AKM-24H	wt-%	9.8%	9.8%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Carbon Dioxide	wt-%	0.0%	0.0%	0.0%	69.7%	69.7%	0.1%	0.1%	96.7%	99.6%	0.0%	0.0%	0.0%	0.0%	0.0%
Nitrogen	wt-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Oxygen	wt-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Argon	wt-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Total Mole Flow	kmol/s	125	125	0.0	6.26	6.26	2.69	0.29	3.28	3.06	0.00	0.00	0.00	7.59	7.59
Total Mass Flow	kg/s	3190	3190	0	192	192	49	5	138	134	0	0	0	137	137
Vapor Fraction		0.00%	0.00%	0.00%	100.00%	52.40%	0.00%	0.00%	100.00%	100.00%				100.00%	0.00%
Liquid Fraction		100.00%	100.00%	100.00%	0.00%	47.60%	100.00%	100.00%	0.00%	0.00%				0.00%	100.00%
Mass Density	kg/m3	1139	1149	998	0.411	0.847	997.880	997.880	0.593	4.83				0.421	966
Average Molecular Weight	kg/kmol	25.43	25.43	18.02	30.61	30.61	18.02	18.02	42.04	43.74				18.02	18.02
Mixture Critical Pressure	bara	193.7	193.7	220.4	149.4	149.4	220.4	220.4	84.9	75.3				220.4	220.4
Mixture Critical Temperature	°C	355.8	355.8	374.1	207.8	207.8	374.1	374.1	57.0	34.5				374.1	374.1
Mixture Heat Capacity	kJ/kg-K	3.36	3.34	4.18	1.19		4.18	4.18	0.88	0.86				1.88	4.20
Mixture CpCv Ratio		1.10	1.05	1.01	1.30	1.09	1.01	1.01	1.29	1.30					1.01
Mass Enthalpy	MJ/kg	-9.61	-9.67	-15.91	-10.26	-11.00	-15.89	-15.89	-9.10	-8.97				-13.32	-15.60
Compressibility Factor					0.9977	0.9980			0.9981	0.9862					
Vapor Standard Volume	m3/kmol				74.5				70.9	9.1				42.8	
Vapor Thermal Conductivity	mW/m-K				20.7	16.4			16.4	16.3					
Mixture Liquid Viscosity	cP	1.10	1.55	1.07		0.80	0.81	0.81							0.25
Liquid Standard Volume	L/kmol	22.3	22.1	18.1			18.1	18.1							18.7
Liquid Surface Tension	mN/m	71.7	75.0	73.3		73.3	73.3	73.3							60.8
Liquid Thermal Conductivity	mW/m-K	1821	1885	594		593	593	593							680
CO2 Capture	%														
AKM-24 Concentration	wt.%	35.0%	35.0%												
CO2 Loading	mol/mol	0.400	0.400												

Stream Table	Stream:	32	33	34	35	36	37	38	39	40	41
Temperature	°C	16.0	27.0	16.0	27.0	16.0	27.0	16.0	27.0	16.0	27.0
Pressure	bara	5.00	4.98	5.00	4.98	5.00	4.98	5.00	4.98	5.00	4.98
Standard Gas Flow [Wet]	Nm3/h*10-6										
Liquid Volume Flow	LPM	634846	635974	163525	163816	254785	255237	184270	184598	32266	32323
Component Mole Fractions:											
Water	mol-%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Potassium Ion	mol-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
AKM-24	mol-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Biocarbonate Ion	mol-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
AKM-24H	mol-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Carbon Dioxide	mol-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Nitrogen	mol-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Oxygen	mol-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Argon	mol-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Component Mass Fractions:											
Water	wt-%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Potassium Ion	wt-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
AKM-24	wt-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Biocarbonate Ion	wt-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
AKM-24H	wt-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Carbon Dioxide	wt-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Nitrogen	wt-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Oxygen	wt-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Argon	wt-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Total Mole Flow	kmol/s	586	586	151	151	235	235	170	170	29.8	29.8
Total Mass Flow	kg/s	10564	10564	2721	2721	4240	4240	3066	3066	537	537
Vapor Fraction		0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Liquid Fraction		100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
Mass Density	kg/m3	998	997	998	997	998	997	998	997	998	997
Average Molecular Weight	kg/kmol	18.02	18.02	18.02	18.02	18.02	18.02	18.02	18.02	18.02	18.02
Mixture Critical Pressure	bara	220.4	220.4	220.4	220.4	220.4	220.4	220.4	220.4	220.4	220.4
Mixture Critical Temperature	°C	374.1	374.1	374.1	374.1	374.1	374.1	374.1	374.1	374.1	374.1
Mixture Heat Capacity	kJ/kg-K	4.18	4.17	4.18	4.17	4.18	4.17	4.18	4.17	4.18	4.17
Mixture CpCv Ratio		1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01
Mass Enthalpy	MJ/kg	-15.91	-15.86	-15.91	-15.86	-15.91	-15.86	-15.91	-15.86	-15.91	-15.86
Compressibility Factor											
Vapor Standard Volume	m3/kmol										
Vapor Thermal Conductivity	mW/m-K										
Mixture Liquid Viscosity	cP	1.07	0.80	1.07	0.80	1.07	0.80	1.07	0.80	1.07	0.80
Liquid Standard Volume	L/kmol	18.0	18.1	18.0	18.1	18.0	18.1	18.0	18.1	18.0	18.1
Liquid Surface Tension	mN/m	73.3	71.6	73.3	71.6	73.3	71.6	73.3	71.6	73.3	71.6
Liquid Thermal Conductivity	mW/m-K	594	612	594	612	594	612	594	612	594	612
CO2 Capture	%										
AKM-24 Concentration	wt.%										
CO2 Loading	mol/mol										

Blowers:		BLR-201	VBLR-301
Number of Stages	--	1	16
Inlet Mass Flow Rate	kg/hr	2425690	496713
Inlet Temperature	C	35.0	21.7
Comp. Ratio Per Stage	--	1.07	1.14
Cp/Cv Ratio		1.30	1.30
Average Molecular Weight		30.05	42.04
Isentropic Efficiency		85%	--
Brake Power	kW	4700	24649
Electric Power Efficiency	%	95.0%	97.0%
Electric Power	kWe	4947	25411
Specific Duty	kWh/tCO2	**10.3**	**52.9**

Columns:		DCC-101	ABS-201	STR-301
Packing Diameter	m	20.0	22.8	17.2
Packing Height	m	3.5	16.4	12.5
Packing Volume	m3	1100	6703	2904
Packing Type	--	IMTP40	M350Y	M350Y
Area Efficiency		0.59	0.50	0.50

Pumps:		Total	P-101	P-201	P-202	P-301	P-302	P-303	P-401	P-402
Description	--	--	DCC Pump	Rich Pump	H2O Mkup	Lean Pump	Reb. Pump	Cond. Pump	Solv. Mkup.	Sump Pump
Mass Flow Rate	kg/hr	--	4390887	11998900	0	11309000	11309000	193166	1199890	1199890
Density	kg/m3	--	986	1202	998	1119	1119	998	1202	1202
Pressure Boost	bara	--	0.20	4.83	2.50	4.83	0.07	2.16	4.83	4.83
Pump Efficiency	%	--	75%	75%	75%	75%	75%	75%	75%	75%
Brake Power	kW	3989	33	1784	0	1807	25.8	15.5	178.4	178.4
Electric Power Efficiency	%	95.0%	95.0%	95.0%	95.0%	95.0%	95.0%	95.0%	95.0%	95.0%
Electric Power	kWe	4199	35	1878	0	1902	27.2	16.3	187.8	187.8
Specific Duty	kWh/tCO2	**8.81**	**0.07**	**3.91**	**0.00**	**3.96**	**0.06**	**0.03**	**0.39**	**0.39**

Exchangers		HX-101	HX-201	HX-301	HX-302	HX-303	REB-301
Description	--	DCC Cooler	Trim Cooler	Cross Exch.	OH Cond.	VBLR Clr.	Reboiler
Cold Side		CW	CW	AKM-24	CW	CW	AKM-24
Hot Side		Wet FG	AKM-24	AKM-24	Wet CO2	Wet CO2	LP Steam
Cold Inlet Temperature	°C	16.0	16.0	44.4	16.0	16.0	79.9
Cold Outlet Temperature	°C	27.0	27.0	74.9	27.0	27.0	79.9
Hot Inlet Temperature	°C	58.0	50.2	79.9	63.7	208.9	89.9
Hot Outlet Temperature	°C	54.3	32.0	50.7	22.0	22.0	89.9
Cold Side Temp. Delta	°C	38.3	16.0	6.25	6.00	6.00	10.0
Hot Side Temp. Delta	°C	31.0	23.2	4.99	36.7	181.9	10.0
Log Mean Temp. Delta	°C	34.5	19.4	5.60	16.9	51.6	10.0
Heat Exchanger Duty	MWth	**-124.9**	**-194.6**	**-309.6**	**-140.8**	**-24.6**	**312.1**
UA Factor	MW/K	3.6	10.0	55.3	8.3	0.478	31.2
Exchanger Specific Duty	GJ/tCO2	**-0.936**	**-1.46**	**-2.32**	**-1.055**	**-0.1847**	**2.34**

Reboiler:		
CO2 Absorbed	t/hr	480.6
CO2 Released	t/hr	480.6
Reboiler Duty	MW	312.1
Specific Reboiler Duty	GJ/tCO2	2.34
Reboiler Temp.	°C	79.9
Steam-to-Power Efficiency	%	12.47%
Equivalent Work	kWh/tCO2	**81.0**

Equivalent Work		
Blowers	kWh/tCO2	10.3
Circulation Pumps	kWh/tCO2	8.8
Reboiler	kWh/tCO2	81.0
Vacuum Blower	kWh/tCO2	52.9
Compressor	kWh/tCO2	76.8
Total Equivalent Work	kWh/tCO2	**229.8**

Exhibit 4-7: Case-2B CO_2 Unit HMB

Stream Table	Stream:	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Temperature	°C	58.0	54.3	35.0	35.0	41.8	32.6	44.3	44.4	44.4	44.4	101.2	83.3	106.4	106.4
Pressure	bara	1.00	1.00	1.20	0.98	1.05	1.03	1.05	5.88	5.88	5.88	5.88	1.06	1.76	1.74
Standard Gas Flow [Wet]	Nm3/h*10-6	2.119			1.903	1.903	1.600								
Liquid Volume Flow	LPM		2781	73367				165865	165850	150476	15374	159017		156310	
Component Mole Fractions:															
Water	mol-%	15.4%	100.0%	100.0%	5.8%	5.8%	4.0%	83.2%	83.2%	83.2%	83.2%	83.2%	83.5%	85.5%	85.5%
Potassium Ion	mol-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	6.0%	6.0%	6.0%	6.0%	6.0%	5.9%	6.2%	6.2%
AKM-24	mol-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	1.2%	1.2%	1.2%	1.2%	1.5%	3.3%	3.9%	3.9%
Biocarbonate Ion	mol-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	4.8%	4.8%	4.8%	4.8%	4.5%	2.6%	2.2%	2.2%
AKM-24H	mol-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	4.8%	4.8%	4.8%	4.8%	4.5%	2.6%	2.2%	2.2%
Carbon Dioxide	mol-%	13.5%	0.0%	0.0%	15.0%	15.0%	1.8%	0.0%	0.0%	0.0%	0.0%	0.3%	2.1%	0.0%	0.0%
Nitrogen	mol-%	67.9%	0.0%	0.0%	75.6%	75.6%	90.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Oxygen	mol-%	2.4%	0.0%	0.0%	2.7%	2.7%	3.2%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Argon	mol-%	0.8%	0.0%	0.0%	0.9%	0.9%	1.1%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Component Mass Fractions:															
Water	wt-%	9.6%	100.0%	100.0%	3.5%	3.5%	2.6%	56.6%	56.6%	56.6%	56.6%	56.8%	58.1%	60.5%	60.5%
Potassium Ion	wt-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	8.9%	8.9%	8.9%	8.9%	8.9%	8.9%	9.4%	9.4%
AKM-24	wt-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	4.6%	4.6%	4.6%	4.6%	5.9%	13.0%	15.8%	15.8%
Biocarbonate Ion	wt-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	11.1%	11.1%	11.1%	11.1%	10.4%	6.1%	5.3%	5.3%
AKM-24H	wt-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	18.8%	18.8%	18.8%	18.8%	17.5%	10.3%	9.0%	9.0%
Carbon Dioxide	wt-%	20.6%	0.0%	0.0%	22.0%	22.0%	2.8%	0.0%	0.0%	0.0%	0.0%	0.5%	3.6%	0.0%	0.0%
Nitrogen	wt-%	66.0%	0.0%	0.0%	70.5%	70.5%	89.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Oxygen	wt-%	2.6%	0.0%	0.0%	2.8%	2.8%	3.6%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Argon	wt-%	1.1%	0.0%	0.0%	1.2%	1.2%	1.5%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Total Mole Flow	kmol/s	24.9	2.54	67.5	22.4	22.4	18.8	126	126	114	12	114	116	111	111
Total Mass Flow	kg/s	718	45.7	1216	672	672	529	3324	3324	3015	308	3015	3015	2836	2836
Vapor Fraction		100.00%	0.00%	0.00%	100.00%	100.00%	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%	3.71%	0.00%	4.45%
Liquid Fraction		0.00%	100.00%	100.00%	0.00%	0.00%	0.00%	100.00%	100.00%	100.00%	100.00%	100.00%	96.29%	100.00%	95.55%
Mass Density	kg/m3	1.05	986	995	1.15	1.21	1.14	1202	1202	1202	1202	1138	24.6	1089	
Average Molecular Weight	kg/kmol	28.83	18.02	18.02	30.05	30.05	28.15	26.46	26.46	26.46	26.46	26.38	25.90	25.46	25.46
Mixture Critical Pressure	bara	68.5	220.5	220.4	51.3	51.3	42.9	189.2	189.2	189.2	189.2	189.4	190.8	193.6	193.6
Mixture Critical Temperature	°C	-41.9	374.1	374.0	-89.1	-89.1	-121.6	352.5	352.5	352.5	352.5	351.9	348.6	355.8	355.8
Mixture Heat Capacity	kJ/kg-K	1.08	4.18	4.17	1.02	1.02	1.05	2.98	2.98	2.98	2.98	3.17		3.50	
Mixture CpCv Ratio		1.37	1.04	1.02	1.38	1.37	1.40	1.13	1.13	1.13	1.13	1.40	1.21	1.00	
Mass Enthalpy	MJ/kg	-3.10	-15.75	-15.83	-2.42	-2.42	-0.59	-9.65	-9.65	-9.65	-9.65	-9.47	-9.47	-9.34	-9.24
Compressibility Factor		0.9986			0.9989	0.9989	0.9993						0.9949		
Vapor Standard Volume	m3/kmol	27.5			26.1	24.9	24.7								
Vapor Thermal Conductivity	mW/m-K	25.2			24.0	24.5	25.4						22.2		
Mixture Liquid Viscosity	cP		0.48	0.67				1.49	1.49	1.49	1.49	0.53	0.64	0.49	
Liquid Standard Volume	L/kmol		18.3	18.1				22.0	22.0	22.0	22.0	23.2		23.4	
Liquid Surface Tension	mN/m		67.0	70.4				71.8	71.7	71.7	71.7	61.6	65.8	57.6	
Liquid Thermal Conductivity	mW/m-K		639	624				709	709	709	709	719	1584	1698	
CO2 Capture	%	0.0%	0.0%		0.0%	0.0%	90.0%								
AKM-24 Concentration	wt.%							34.9%	34.9%	34.9%	34.9%	34.9%	34.9%	35.5%	35.4%
CO2 Loading	mol/mol							0.800	0.800	0.800	0.800	0.748	0.438	0.359	0.400

Stream Table	Stream:	15	16	17	18	19	20	21	22	23	24	25	26	27	28
Temperature	°C	106.4	50.7	50.2	50.0	32.0	16.0	84.9	30.0	29.9	29.9	29.9	30.0	--	--
Pressure	bara	1.07	1.07	1.07	2.50	2.48	3.50	1.05	1.03	2.50	2.50	1.02	8.17	--	--
Standard Gas Flow [Wet]	Nm3/h*10-6							0.476				0.269	0.259		
Liquid Volume Flow	LPM	156310	150019	165410	167598	166072	0			2214	436			0	0
Component Mole Fractions:															
Water	mol-%	85.5%	85.5%	85.3%	85.5%	85.5%	100.0%	45.9%	45.9%	99.9%	99.9%	4.2%	0.6%	0.0%	0.0%
Potassium Ion	mol-%	6.2%	6.2%	6.1%	6.0%	6.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
AKM-24	mol-%	3.9%	3.9%	3.7%	3.6%	3.6%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Biocarbonate Ion	mol-%	2.2%	2.2%	2.5%	2.4%	2.4%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
AKM-24H	mol-%	2.2%	2.2%	2.5%	2.4%	2.4%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Carbon Dioxide	mol-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	54.1%	54.1%	0.1%	0.1%	95.8%	99.4%	0.0%	0.0%
Nitrogen	mol-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Oxygen	mol-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Argon	mol-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Component Mass Fractions:															
Water	wt-%	60.5%	60.5%	60.1%	60.6%	60.6%	100.0%	25.8%	25.8%	99.9%	99.9%	1.8%	0.2%	0.0%	0.0%
Potassium Ion	wt-%	9.4%	9.4%	9.4%	9.3%	9.3%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
AKM-24	wt-%	15.8%	15.8%	14.7%	14.6%	14.6%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Biocarbonate Ion	wt-%	5.3%	5.3%	5.9%	5.8%	5.8%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
AKM-24H	wt-%	9.0%	8.9%	9.9%	9.8%	9.8%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Carbon Dioxide	wt-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	74.2%	74.2%	0.1%	0.1%	98.2%	99.8%	0.0%	0.0%
Nitrogen	wt-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Oxygen	wt-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Argon	wt-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Total Mole Flow	kmol/s	111	111	123	125	125	0.0	5.59	5.59	2.04	0.40	3.16	3.04	0.00	0.00
Total Mass Flow	kg/s	2836	2836	3144	3181	3181	0	179	179	37	7	135	133	0	0
Vapor Fraction		0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%	56.43%	0.00%	0.00%	100.00%	100.00%		
Liquid Fraction		100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	0.00%	43.57%	100.00%	100.00%	0.00%	0.00%		
Mass Density	kg/m3	1089	1134	1140	1139	1149	998	1.137	2.333	995.109	995.109	1.746	14.80		
Average Molecular Weight	kg/kmol	25.46	25.46	25.55	25.43	25.43	18.03	32.07	32.07	18.03	18.03	42.91	43.86		
Mixture Critical Pressure	bara	193.6	193.6	193.2	193.7	193.7	220.4	141.1	141.1	220.4	220.4	79.9	74.6		
Mixture Critical Temperature	°C	355.8	355.8	355.5	355.8	355.8	374.0	188.6	188.6	374.0	374.0	45.4	33.0		
Mixture Heat Capacity	kJ/kg-K	3.50	3.39	3.35	3.36	3.34	4.18	1.16		4.18	4.18	0.87	0.89		
Mixture CpCv Ratio		1.00	1.10	1.10	1.10	1.05	1.02	1.29	1.11	1.02	1.02	1.29	1.33		
Mass Enthalpy	MJ/kg	-9.34	-9.53	-9.54	-9.61	-9.67	-15.90	-10.04	-10.69	-15.85	-15.85	-9.02	-8.96		
Compressibility Factor								0.9948	0.9949			0.9950	0.9606		
Vapor Standard Volume	m3/kmol							28.2				24.6	3.0		
Vapor Thermal Conductivity	mW/m-K							22.4	17.0			17.0	16.9		
Mixture Liquid Viscosity	cP	0.49	1.16	1.12	1.11	1.55	1.07		0.70	0.70	0.70				
Liquid Standard Volume	L/kmol	23.4	22.4	22.4	22.3	22.1	18.1			18.1	18.1				
Liquid Surface Tension	mN/m	61.9	71.8	71.8	71.8	75.0	73.3		71.7	71.7	71.7				
Liquid Thermal Conductivity	mW/m-K	1698	1962	1839	1821	1885	594		586	586	586				
CO2 Capture	%														
AKM-24 Concentration	wt.%	35.5%	35.5%	35.4%	35.0%	35.0%									
CO2 Loading	mol/mol	0.359	0.359	0.400	0.400	0.400									

Stream Table	Stream:	29	30	31	32	33	34	35	36	37	38	39	40	41
Temperature	°C	--	116.4	116.4	16.0	27.0	16.0	27.0	16.0	27.0	16.0	27.0	16.0	27.0
Pressure	bara	--	1.77	1.76	5.00	4.98	5.00	4.98	5.00	4.98	5.00	4.98	5.00	4.98
Standard Gas Flow [Wet]	Nm3/h*10-6		0.604											
Liquid Volume Flow	LPM	0		8163	607133	608212	163058	163348	251381	251828	154193	154467	38500	38569
Component Mole Fractions:														
Water	mol-%	0.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Potassium Ion	mol-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
AKM-24	mol-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Biocarbonate Ion	mol-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
AKM-24H	mol-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Carbon Dioxide	mol-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Nitrogen	mol-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Oxygen	mol-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Argon	mol-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Component Mass Fractions:														
Water	wt-%	0.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
Potassium Ion	wt-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
AKM-24	wt-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Biocarbonate Ion	wt-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
AKM-24H	wt-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Carbon Dioxide	wt-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Nitrogen	wt-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Oxygen	wt-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Argon	wt-%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Total Mole Flow	kmol/s	0.00	7.09	7.09	561	561	151	151	232	232	142	142	35.6	35.6
Total Mass Flow	kg/s	0	128	128	10102	10102	2713	2713	4183	4183	2566	2566	641	641
Vapor Fraction			100.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Liquid Fraction			0.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
Mass Density	kg/m3		1.008	939	998	997	998	997	998	997	998	997	998	997
Average Molecular Weight	kg/kmol		18.02	18.02	18.02	18.02	18.02	18.02	18.02	18.02	18.02	18.02	18.02	18.02
Mixture Critical Pressure	bara		220.4	220.4	220.4	220.4	220.4	220.4	220.4	220.4	220.4	220.4	220.4	220.4
Mixture Critical Temperature	°C		374.0	374.0	374.0	374.0	374.0	374.0	374.0	374.0	374.0	374.0	374.0	374.0
Mixture Heat Capacity	kJ/kg-K		1.90	4.20	4.18	4.17	4.18	4.17	4.18	4.17	4.18	4.17	4.18	4.17
Mixture CpCv Ratio				1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02	1.02
Mass Enthalpy	MJ/kg		-13.27	-15.49	-15.90	-15.86	-15.90	-15.86	-15.90	-15.86	-15.90	-15.86	-15.90	-15.86
Compressibility Factor														
Vapor Standard Volume	m3/kmol		17.9											
Vapor Thermal Conductivity	mW/m-K													
Mixture Liquid Viscosity	cP			0.13	1.07	0.80	1.07	0.80	1.07	0.80	1.07	0.80	1.07	0.80
Liquid Standard Volume	L/kmol			19.2	18.0	18.1	18.0	18.1	18.0	18.1	18.0	18.1	18.0	18.1
Liquid Surface Tension	mN/m			55.6	73.3	71.6	73.3	71.6	73.3	71.6	73.3	71.6	73.3	71.6
Liquid Thermal Conductivity	mW/m-K			692	594	612	594	612	594	612	594	612	594	612
CO2 Capture	%													
AKM-24 Concentration	wt.%													
CO2 Loading	mol/mol													

Blowers:		BLR-201	VBLR-301
Number of Stages	--	1	1
Inlet Mass Flow Rate	kg/hr	2418760	487779
Inlet Temperature	C	35.0	29.9
Comp. Ratio Per Stage	--	1.07	8.04
Cp/Cv Ratio		1.30	1.30
Average Molecular Weight		30.05	42.91
Isentropic Efficiency		85%	80%
Brake Power	kW	4686	23601
Electric Power Efficiency	%	95.0%	97.0%
Electric Power	kWe	4933	24331
Specific Duty	kWh/tCO2	**10.3**	**50.8**

Columns:		DCC-101	ABS-201	STR-301
Packing Diameter	m	20.0	22.8	14.4
Packing Height	m	3.5	16.4	10.0
Packing Volume	m3	1100	6677	1633
Packing Type	--	IMTP40	M350Y	M350Y
Area Efficiency		0.59	0.50	0.50

Pumps:		Total	P-101	P-201	P-202	P-301	P-302	P-303	P-401	P-402
Description	--	--	DCC Pump	Rich Pump	H2O Mkup	Lean Pump	Reb. Pump	Cond. Pump	Solv. Mkup.	Sump Pump
Mass Flow Rate	kg/hr	--	4378815	11964600	0	10209500	10209500	158176	1196460	1196460
Density	kg/m3	--	986	1202	998	1089	1089	995	1202	1202
Pressure Boost	bara	--	0.20	4.83	2.50	4.83	0.69	1.48	4.83	4.83
Pump Efficiency	%	--	75%	75%	75%	75%	75%	75%	75%	75%
Brake Power	kW	4059	33	1779	0	1676	239.5	8.7	177.9	177.9
Electric Power Efficiency	%	95.0%	95.0%	95.0%	95.0%	95.0%	95.0%	95.0%	95.0%	95.0%
Electric Power	kWe	4273	35	1873	0	1765	252.1	9.2	187.3	187.3
Specific Duty	kWh/tCO2	**8.99**	**0.07**	**3.91**	**0.00**	**3.68**	**0.53**	**0.02**	**0.39**	**0.39**

Exchangers		HX-101	HX-201	HX-301	HX-302	HX-303	REB-301
Description	--	DCC Cooler	Trim Cooler	Cross Exch.	OH Cond.	Precomp. Clr.	Reboiler
Cold Side		CW	CW	AKM-24	CW	CW	AKM-24
Hot Side		Wet FG	AKM-24	AKM-24	Wet CO2	Wet CO2	LP Steam
Cold Inlet Temperature	°C	16.0	16.0	44.4	16.0	16.0	106.4
Cold Outlet Temperature	°C	27.0	27.0	101.2	27.0	27.0	106.4
Hot Inlet Temperature	°C	58.0	50.0	106.4	84.9	215.6	116.4
Hot Outlet Temperature	°C	54.3	32.0	50.7	30.0	30.0	116.4
Cold Side Temp. Delta	°C	38.3	16.0	6.35	14.00	14.00	10.0
Hot Side Temp. Delta	°C	31.0	23.0	5.18	57.9	188.6	10.0
Log Mean Temp. Delta	°C	34.5	19.3	5.75	30.9	67.1	10.0
Heat Exchanger Duty	MWth	**-124.6**	**-192.0**	**-543.0**	**-117.8**	**-29.4**	**282.7**
UA Factor	MW/K	3.6	9.9	94.5	3.8	0.438	28.3
Exchanger Specific Duty	GJ/tCO2	**-0.936**	**-1.44**	**-4.08**	**-0.885**	**-0.2210**	**2.12**

Reboiler:		
CO2 Absorbed	t/hr	479.2
CO2 Released	t/hr	479.3
Reboiler Duty	MW	282.7
Specific Reboiler Duty	GJ/tCO2	2.12
Reboiler Temp.	°C	106.4
Steam-to-Power Efficiency	%	17.62%
Equivalent Work	kWh/tCO2	**103.9**

Equivalent Work		
Blowers	kWh/tCO2	10.3
Circulation Pumps	kWh/tCO2	9.0
Reboiler	kWh/tCO2	103.9
Vacuum Blower	kWh/tCO2	50.8
Compressor	kWh/tCO2	53.1
Total Equivalent Work	kWh/tCO2	**227.0**

Accounting of auxiliary loads, cooling, and chemicals are presented in Exhibit 4-8.

Exhibit 4-8: Comparative Plant Performance Summary

	BBS Case 11	BBS Case 12	AKM24 Case 1A	AKM24 Case 2A	AKM24 Case 2B
Steam Turbine Gross Power	580,400	662,800	694,166	662,785	649,872
AUXILIARY LOAD SUMMARY, kWe					
Coal Handling and Conveying	440	510	454	444	442
Pulverizers	2,780	3,850	3,504	3,386	3,371
Sorbent Handling & Reagent Preparation	890	1,250	1,140	1,100	1,095
Ash Handling	530	740	674	651	648
Primary Air Fans	1,300	1,800	1,638	1,582	1,576
Forced Draft Fans	1,660	2,300	2,093	2,023	2,015
Induced Draft Fans	7,050	11,120	10,258	9,835	9,800
SCR	50	70	64	62	62
Baghouse	70	100	91	88	88
Wet FGD	2,970	4,110	3,740	3,614	3,599
CO_2 Vacuum Blower	0	0	32,233	25,458	0
CO_2 Capture System Auxiliaries	0	20,600	9,842	9,306	9,135
CO_2 Compression	0	44,890	59,319	36,996	49,955
Miscellaneous Balance of Plant	2,000	2,000	1,738	1,725	1,713
Steam Turbine Auxiliaries	400	400	409	396	387
Condensate Pumps	800	560	533	609	652
Circulating Water Pumps	4,730	10,100	8,682	8,178	8,093
Ground Water Pumps	480	910	847	805	803
Cooling Tower Fans	2,440	5,230	4,496	4,235	4,191
Transformer Loss	1,820	2,290	2,411	2,294	2,248
TOTAL AUXILIARIES, kWe	**30,410**	**112,830**	**144,166**	**112,785**	**99,872**
NET PLANT POWER	549,990	549,970	550,000	550,000	550,000
Net Plant Efficiency (HHV)	39.3%	28.4%	31.3%	32.3%	32.5%
Net Plant Heat Rate, Btu/kWh (HHV)	8,687	12,002	10,918	10,553	10,506
Net Plant Heat Rate, kJ/kWh (HHV)	9,165	12,663	11,520	11,134	11,084
CONDENSER COOLING DUTY, MMBtu/hr	2,178	1,646	1,603	1,721	1,845
CONDENSER COOLING DUTY, kWth	638,309	482,395	469,904	504,252	540,834
CO_2 Capture					
Flue Gas Flow (into capture system), lb/hr	4,713,221	6,518,035	5,930,482	5,731,174	5,706,685
Flue Gas Flow (into capture system), kg/hr	2,137,917	2,956,581	2,690,067	2,599,661	2,588,553
CO_2 Captured, lb/hr	N/A	1,209,158	1,096,567	1,061,585	1,061,516
CO_2 Captured,kg/hr	N/A	548,474	497,403	481,535	481,504
Steam Extracted for CO_2 Capture System					
Flow, lb/hr	N/A	1,784,175	1,292,436	1,085,145	1,012,736
Flow, kg/hr	N/A	809,302	586,249	492,222	459,377
Temperature, °F	N/A	556	158	194	242
Temperature, °C	N/A	291	70	90	116
Pressure, psia	N/A	73.5	4.6	10.1	25.5
Pressure, MPa	N/A	0.51	0.03	0.07	0.18
CONSUMABLES					
As-Received Coal Feed, lb/hr	409,528	565,820	514,815	497,514	495,388
As-Received Coal Feed, kg/hr	185,762	256,656	233,520	225,672	224,708
Limestone Sorbent Feed, lb/hr	40,667	57,245	52,085	50,334	50,119
Limestone Sorbent Feed, kg/hr	18,446	25,966	23,626	22,832	22,734

Thermal Input, kWth	1,400,162	1,934,519	1,760,136	1,700,983	1,693,715
Raw Water Withdrawal, gpm	5,321	10,072	8,457	8,124	8,038
Raw Water Withdrawal, m3/hr	1,209	2,288	1,921	1,845	1,826
Raw Water Consumption, gpm	4,227	7,733	6,510	6,256	6,191
Raw Water Consumption, m3/hr	960	1,756	1,479	1,421	1,406

Notes:

A. ΔP, ΔT for steam from STG to PCC is not accounted, similar to the Baseline report.

B. In the BBS Report Case 11, LP turbine exhaust steam quality is approximately 76%, which is lower than what is typically recommended by ST OEM (~90%). The LP turbine steam exhaust quality of ~91% for AKM cases is within the recommended range and consistent with the BBS Report Case 12.

C. Case-1A (and other AKM cases) auxiliary load for coal handling system was estimated based on Case 12 specific aux. load of 0.0009 kWh per 1 lb. of coal handled.

Air emissions, water balance, carbon balance, sulphur balance, and water balance for the Akermin AKM24 cases are reported in Exhibit 4-9 through Exhibit 4-12 below.

Exhibit 4-9: Air Emissions

Air Emissions	kg/GJ	lb/10^6 Btu	tonne/yr 85% CF	ton/yr 85% CF	kg/MWh	lb/MWh
Case 12						
SO_2	0.001	0.002	36	40	0.007	0.02
Nox	0.03	0.07	1561	1720	0.316	0.697
Particulates	0.006	0.013	290	319	0.059	0.129
Hg	4.91E-07	1.14E-06	0.025	0.028	5.16E-06	1.14E-05
CO_2	8.8	20.4	453,763	500,188	92	203
CO_2 (net)					111	244
Case-1A						
SO_2	TBD	TBD	TBD	TBD	TBD	TBD
Nox	TBD	TBD	TBD	TBD	TBD	TBD
Particulates	TBD	TBD	TBD	TBD	TBD	TBD
Hg	TBD	TBD	TBD	TBD	TBD	TBD
CO_2	8.7	20.2	410,911	452,824	79	175
CO_2 (net)					98	215
Case-2A						
SO_2	TBD	TBD	TBD	TBD	TBD	TBD
Nox	TBD	TBD	TBD	TBD	TBD	TBD
Particulates	TBD	TBD	TBD	TBD	TBD	TBD
Hg	TBD	TBD	TBD	TBD	TBD	TBD
CO_2	8.7	20.3	397,864	438,446	81	178
CO_2 (net)					96	212
Case-2B						
SO_2	TBD	TBD	TBD	TBD	TBD	TBD
Nox	TBD	TBD	TBD	TBD	TBD	TBD
Particulates	TBD	TBD	TBD	TBD	TBD	TBD
Hg	TBD	TBD	TBD	TBD	TBD	TBD
CO_2	8.7	20.3	396,716	437,181	82	181
CO_2 (net)					96	211

Exhibit 4-10: Water Balance

Water Use	Water Demand		Internal Recycle		Raw Water Withdrawal		Process Water Discharge		Raw Water Consumption	
	m^3/min	gpm	m^3/min	gpm	m^3/min	gpm	m^3/min	gpm	m^3/min	gpm
Case 12										
CO_2 Unit	0.1	36	0.0	0.0	0.1	36	0.0	0.0	0.1	36
FGD Makeup	5.1	1,340	0.0	0.0	5.1	1,340	0.0	0.0	5.1	1,340
BFW Makeup	0.0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cooling Tower	39.4	10,399	6.5	1,703	32.9	8,696	8.9	2,339	24.1	6,357
Total	**44.6**	**11,774**	**6.5**	**1,703**	**38.1**	**10,071**	**8.9**	**2,339**	**29.3**	**7,733**
Case-1A										
CO_2 Unit	0.1	24	0.0	0	0.1	24	0.0	0	0.1	24
FGD Makeup	4.6	1,226	0.0	0	4.6	1,226	0.0	0	4.6	1,226
BFW Makeup	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0
Cooling Tower	33.2	8,768	5.9	1,562	27.3	7,205	7.4	1,947	19.9	5,259
Total	**37.9**	**10,017**	**5.9**	**1,562**	**32.0**	**8,455**	**7.4**	**1,947**	**24.6**	**6,508**
Case-2A										
CO_2 Unit	0.1	21	0.0	0	0.1	21	0.0	0	0.1	21
FGD Makeup	4.0	1,051	0.0	0	4.0	1,051	0.0	0	4.0	1,051
BFW Makeup	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0
Cooling Tower	31.8	8,390	5.1	1,339	26.7	7,051	7.1	1,867	19.6	5,184
Total	**35.8**	**9,461**	**5.1**	**1,339**	**30.7**	**8,122**	**7.1**	**1,867**	**23.7**	**6,255**
Case-2B										
CO_2 Unit	0.1	18	0.0	0	0.1	18	0.0	0	0.1	18
FGD Makeup	3.4	911	0.0	0	3.4	911	0.0	0	3.4	911
BFW Makeup	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0
Cooling Tower	31.3	8,268	4.4	1,161	26.9	7,107	7.0	1,847	19.9	5,261
Total	**34.8**	**9,197**	**4.4**	**1,161**	**30.4**	**8,036**	**7.0**	**1,847**	**23.4**	**6,189**

Exhibit 4-11: Carbon Balance

Carbon Balance	30% MEA Case 12		AKM-24 Case-1A		AKM-24 Case-2A		AKM-24 Case-2B	
Carbon In	kg/hr	lb/hr	kg/hr	lb/hr	kg/hr	lb/hr	kg/hr	lb/hr
Coal	163,602	360,579	148,854	328,075	143,852	317,050	143,238	315,696
Air (CO_2)	355	782	323	712	312	688	311	685
FGD Reagent	2,635	5,808	2,397	5,284	2,317	5,106	2,307	5,085
Total	**166,592**	**367,169**	**151,575**	**334,071**	**146,481**	**322,844**	**145,855**	**321,465**
Carbon Out								
Stack Gas	16,632	36,657	15,050	33,171	14,572	32,118	14,530	32,025
FGD Product	274	604	249	549	241	531	240	529
CO_2 Product	149,685	329,906	136,275	300,351	131,668	290,196	131,085	288,911
Total	**166,592**	**367,169**	**151,575**	**334,071**	**146,481**	**322,844**	**145,855**	**321,465**

Exhibit 4-12: Sulphur Balance

Sulfur Balance	30% MEA Case 12		AKM-24 Case-1A		AKM-24 Case-2A		AKM-24 Case-2B	
Sulphur In	kg/hr	lb/hr	kg/hr	lb/hr	kg/hr	lb/hr	kg/hr	lb/hr
Coal	6,433	14,178	5,853	12,900	5,656	12,467	5,632	12,414
Total	**6,433**	**14,178**	**5,853**	**12,900**	**5,656**	**12,467**	**5,632**	**12,414**
Sulphur Out								
FGD Product	6,304	13,895	5,736	12,643	5,543	12,218	5,520	12,165
Stack Gas	2	5	2	5	2	5	2	5
Polishing Scrubber/HSS	126	278	115	253	111	244	110	243
Total	**6,433**	**14,178**	**5,853**	**12,900**	**5,656**	**12,467**	**5,632**	**12,414**

Exhibit 4-13: Product CO_2 Characteristics relative to pipeline specification [1], [4]

Parameter	Units	CO_2 Pipeline Specification	Case-1A	Case-2A	Case-2B
Inlet Pressure	psia	2215	2215	2215	2215
	Mpa	15.23	15.23	15.23	15.23
Inlet Temperature	°F	95	95	95	95
	°C	35	35	35	35
CO_2, min	vol-%	95	99.99	99.98	99.99
H_2O, max	ppmv	150	0.33	0.33	0.33
N_2, max	ppmv Dry	300	135.3	145	131.5
O_2, max	ppmv Dry	40	8.53	9.51	8.63
Ar, max	ppmv Dry	10	3.10	3.50	3.18

5. EQUIVALENT WORK ANALYSIS.

This project has a goal to optimize cases to achieve < 220 kWh/tCO_2 equivalent work. An extensive study on total equivalent work using AKM-24 as a CO_2 capture solvent has been reported previously in the "Milestone F" report submitted for this project. As a summary, total equivalent work, Equation (1), is defined as the sum of all electrical parasitic power requirements for the CO_2 capture system (CO_2 compression power, vacuum compressor power, circulation pumping power, flue gas blower power) plus the "equivalent work" of extraction steam for solvent regeneration. Equation (2) below defines the steam to power efficiency that is used to calculate equivalent work from the extraction steam heat rates in this study. Equation (2) assumes a 90% factor times the Ideal Carnot Efficiency (maximum efficiency estimate). Equation (2) also assumes a condenser temperature of 40°C (i.e., the cold reservoir), and a 10°C difference between extraction steam temperature and reboiler temperature:

$$\dot{W}_{\text{Total}} = \dot{W}_{\text{ID Fan}} + \dot{W}_{\text{Circ.Pumps}} + \dot{W}_{\text{Steam}} + \dot{W}_{\text{Vac.Pump}} + \dot{W}_{\text{Compression}} \tag{1}$$

Where $\dot{W}_{\text{Steam}}$ is defined as:

$$\dot{W}_{\text{steam}} = \mathbf{0.90}\left[1 - \frac{\mathbf{40}° + 273.15}{T_{Reb} + \mathbf{10}° + 273.15}\right] \dot{Q}_{Steam} \tag{2}$$

Equation-2 above was used to calculate the equivalent work of steam extraction, which is subsequently added to electrical power loads for CO_2 capture system to determine the total equivalent work as shown in Exhibit 5-1. This table is updated based on CO_2 compressor power estimates from MAN Diesel and Turbo (Jan '15 cases) and compared against original estimates (Nov '14 cases).

Exhibit 5-1: Total Equivalent Work Estimates (kWh/tonne CO_2); Various Cases

Equivalent Work (kWh/tCO_2)	NETL-12.2 30% MEA	Case-1A v1 (Nov '14) AKM-24	Case-1A v2 (Jan '15) AKM-24	Case-2A v1 (Nov '14) AKM-24	Case-2A v2 (Jan '15) AKM-24	Case-2B v1 (Nov '14) AKM-24	Case-2B v2 (Jan '15) AKM-24
Reboiler	235.9	61.7	61.7	81.0	81.0	103.9	103.9
ID Fan	37.5	8.7	8.7	10.3	10.3	10.3	10.3
Circulation Pumps		10.8	10.8	8.8	8.8	9.0	9.0
Separation Unit†	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Vacuum Blower	0.0	74.9	64.8	37.2	52.9	10.3	0.0
CO_2 Compressor	81.8	81.8	119.2	81.8	76.8	81.9	103.8
Total Work	**355.2**	**237.9**	**265.2**	**219.1**	**229.8**	**215.4**	**227.0**

†BRS is not expected to contribute significantly to the total equivalent work based on preliminary technology selection. Actual contribution will be considered in the Final TEA.

Notably, Case-2B is again the best performing case, and results suggest there is good potential to achieve the goal of <220 kWh/tCO_2 total equivalent work with further process optimization and development. It is also noted that while the axial-radial compressors quoted by MAN Diesel & Turbo had a considerably lower capital cost, the energy required for operation was higher than anticipated, observed in Exhibit 5-1. This is mainly due to the lack of interstage cooling on these machines, which leads to higher gas discharge temperatures and greater power requirements.

Initial parasitic power (or equivalent work) estimates showed that Cases 2A and 2B were able to achieve between 219 and 215 kWh/t CO_2—both meeting the project goal. However, the new results are between 230 and 227 kWh/t CO_2 for Cases-2A and 2B, respectively. The MAN Turbo compressor technology specified in this updated analysis benefits from high polytropic efficiencies (Case 1A: AV100-16, 86.4% efficiency; Case 2A: AV90-16, 87% efficiency; and Case 2B: AV-71-16, 88% efficiency) using an axial-radial type machine but lacks inter-stage cooling, as previously noted. While the polytropic efficiencies were best in class and the capital costs are quite attractive, the power demand was higher than in our initial modeling. Future work will examine compressor equipment options that include interstage cooling, or the process could be optimized with compressor heat recovery (since operating at lower temperature than MEA, there is a greater potential benefit) to reduce total equivalent work. Alternative equipment may also be considered where high polytropic efficiencies (>85%) are available with low capital cost.

6. COST ESTIMATING RESULTS

The cost estimating methodology used in this TEA study is described in Section 2.7 of the BBS report [2], with updates presented in reference [3]. Given the current level of maturity of the Akermin technology (large bench-scale), a process contingency of 30% was applied to the AKM24 CO_2 capture system capital costs. By contrast, a 20% process contingency was applied for the reference case (NETL Case-12). The maturity level of Case-12 in the BBS report was judged to be "process unproven at commercial scale for power plant applications, but full-size modules have been operated."

Akermin systems include a biocatalyst consumption charge. This charge is a product of biocatalyst production cost assumptions (considering enzyme, immobilization materials, and processing costs) and biocatalyst consumption rate. The consumption rate assumes Akermin's long-term development goal of 12-month biocatalyst half-life. Exhibit 6-1 displays the calculation of unit biocatalyst charge ($/t CO_2) based on 12-month half-life. Additionally, it is also noted that solvent cost is separately calculated based on the expected conversion of solvent into heat stable salts. For this study a charge of $4/kg solvent (as pure salt) is used.

Exhibit 6-1: Biocatalyst Cost Charge for Akermin Cases

Biocatalyst Cost		Case-1A	Case-2A	Case-2B
Biocatalyst Charge	$/t$CO_2$	$0.79	$0.46	$0.43
CO_2 Capture Rate	tCO_2/year	3,968,178	3,588,754	3,573,432
Annual BC Cost	$/year	$2,926,457	$1,653,199	$1,544,540

Exhibit 6-2 show a capital cost summary for Akermin CO_2 capture systems equipped with AKM24 solvent compared to BBS Case-11 (no capture) and Case-12 (capture with 30% MEA).

Total plant capital costs for the AKM24 design cases organized by cost account are presented in Exhibit 6-3 through

Exhibit 6-5. Initial and annual O&M costs are provided in Exhibit 6-6 through Exhibit 6-8.

Exhibit 6-2: Summary of Capital and Operating Costs (2011 USD x 1000)

Item	BBS Case 11	BBS Case 12	AKM-24 Case-1A	AKM-24 Case-2A	AKM-24 Case-2B
Capital Costs					
Total Plant Costs (TPC)	$1,089,771	$1,959,399	$1,885,345	$1,694,964	$1,679,074
Total Overnight Costs (TOC)	$1,348,443	$2,414,734	$2,324,630	$2,089,890	$2,070,298
Total As-spent Capital (TASC)	$1,529,135	$2,752,796	$2,659,199	$2,391,595	$2,369,260
Annual Operating Costs					
Fixed Costs	$38,329	$64,138	$62,336	$56,787	$56,324
Variable Costs	$31,688	$54,089	$50,083	$46,618	$46,248
Fuel Costs	$104,591	$144,504	$131,460	$127,065	$126,495

Exhibit 6-3: Case-1A Total Plant Cost Summary

Acct No.	Item/Description	Equipment Cost	Material Cost	Labor Direct	Labor Indirect	Sales Tax	Bare Erected Cost $	Eng'g CM H.O.& Fee	Contingencies Process	Contingencies Project	TOTAL PLANT COST $	TOTAL PLANT COST $/kW
1	COAL & SORBENT HANDLING	$23,129	$5,890	$13,645	$0	$0	**$42,665**	$3,742	$0	$6,961	**$53,368**	$97
2	COAL & SORBENT PREP & FEED	$15,579	$870	$3,903	$0	$0	**$20,353**	$1,730	$0	$3,312	**$25,396**	$46
3	FEEDWATER & MISC. BOP SYSTEMS	$61,741	$0	$28,690	$0	$0	**$90,431**	$8,042	$0	$16,114	**$114,587**	$208
4	PC BOILER											
4.1	PC Boiler & Accessories	$216,581	$0	$123,407	$0	$0	**$339,987**	$32,722	$0	$37,271	**$409,980**	$745
4.2	SCR (w/4.1)	$0	$0	$0	$0	$0	**$0**	$0	$0	$0	**$0**	$0
4.3	Open	$0	$0	$0	$0	$0	**$0**	$0	$0	$0	**$0**	$0
4.4-4.9	Boiler BoP (w/ ID Fans)	$0	$0	$0	$0	$0	**$0**	$0	$0	$0	**$0**	$0
	SUBTOTAL 4	**$216,581**	**$0**	**$123,407**	**$0**	**$0**	**$339,987**	**$32,722**	**$0**	**$37,271**	**$409,980**	**$745**
5	FLUE GAS CLEANUP	$113,513	$0	$38,411	$0	$0	**$151,924**	$14,167	$0	$16,609	**$182,700**	$332
5B	CO2 REMOVAL & COMPRESSION	$253,485	$38,001	$68,408	$0	$0	**$359,894**	$33,008	$94,705	$97,522	**$585,129**	$1,064
6	COMBUSTION TURBINE/ACCESSORIES											
6.1	Combustion Turbine Generator	N/A	$0	N/A	$0	$0	**$0**	$0	$0	$0	**$0**	$0
6.2-6.9	Combustion Turbine Other	$0	$0	$0	$0	$0	**$0**	$0	$0	$0	**$0**	$0
	SUBTOTAL 6	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**
7	HRSG, DUCTING & STACK											
7.1	Heat Recovery Steam Generator	N/A	$0	N/A	$0	$0	**$0**	$0	$0	$0	**$0**	$0
7.2-7.9	HRSG Accessories, Ductwork and Stack	$21,194	$1,097	$14,177	$0	$0	**$36,468**	$3,252	$0	$5,219	**$44,938**	$82
	SUBTOTAL 7	**$21,194**	**$1,097**	**$14,177**	**$0**	**$0**	**$36,468**	**$3,252**	**$0**	**$5,219**	**$44,938**	**$82**
8	STEAM TURBINE GENERATOR											
8.1	Steam TG & Accessories	$72,926	$0	$8,985	$0	$0	**$81,912**	$7,191	$0	$8,910	**$98,013**	$178
8.2-8.9	Turbine Plant Auxiliaries and Steam Piping	$32,359	$1,370	$17,042	$0	$0	**$50,771**	$4,128	$0	$7,879	**$62,778**	$114
	SUBTOTAL 8	**$105,285**	**$1,370**	**$26,027**	**$0**	**$0**	**$132,683**	**$11,319**	**$0**	**$16,789**	**$160,791**	**$292**
9	COOLING WATER SYSTEM	$21,357	$10,703	$19,191	$0	$0	**$51,251**	$4,692	$0	$7,551	**$63,494**	$115
10	ASH/SPENT SORBENT HANDLING SYS	$6,296	$186	$8,174	$0	$0	**$14,656**	$1,364	$0	$1,647	**$17,667**	$32
11	ACCESSORY ELECTRIC PLANT	$35,062	$15,018	$39,624	$0	$0	**$89,703**	$7,703	$0	$12,203	**$109,610**	$199
12	INSTRUMENTATION & CONTROL	$11,426	$0	$11,459	$0	$0	**$22,884**	$2,021	$1,144	$3,211	**$29,260**	$53
13	IMPROVEMENTS TO SITE	$3,598	$2,069	$7,714	$0	$0	**$13,381**	$1,328	$0	$2,942	**$17,651**	$32
14	BUILDINGS & STRUCTURES	$0	$29,023	$27,526	$0	$0	**$56,549**	$4,994	$0	$9,231	**$70,774**	$129
	TOTAL COST	**$878,226**	**$107,429**	**$404,080**	**$0**	**$0**	**$1,389,735**	**$127,067**	**$122,094**	**$246,449**	**$1,885,345**	**$3,428**
	Owner's Costs											
	Preproduction Costs											
	6 Months All Labor										$12,280	
	1 Month Maintenance Materials										$1,504	
	1 Month Non-fuel Consumables										$2,281	
	1 Month Waste Disposal										$389	
	25% of 1 Months Fuel Cost at 100% CF										$2,739	
	2% of TPC										$37,707	
	Total										**$56,899**	
	Inventory Capital											
	60 day supply of fuel & consumables at 100% CF										$29,076	
	0.5% of TPC (spare parts)										$9,427	
	Total										**$38,502**	
	Initial Cost for Catalyst and Chemicals										$14,027	
	Land										$900	
	Other Owner's Costs										$278,776	
	Financing Costs										$50,180	
	Total Overnight Costs (TOC)										**$2,324,630**	
	TASC Multiplier								(IOU, high-risk, 35 year)		1.14	
	Total As-Spent Cost (TASC)										**$2,659,198**	

Exhibit 6-4: Case-2A Total Plant Costs Summary

Acct No.	Item/Description	Equipment Cost	Material Cost	Labor Direct	Labor Indirect	Sales Tax	Bare Erected Cost $	Eng'g CM H.O.& Fee	Contingencies Process	Contingencies Project	TOTAL PLANT COST $	TOTAL PLANT COST $/kW
1	COAL & SORBENT HANDLING	$22,638	$5,765	$13,356	$0	$0	**$41,759**	$3,663	$0	$6,813	**$52,235**	$95
2	COAL & SORBENT PREP & FEED	$15,250	$852	$3,821	$0	$0	**$19,923**	$1,694	$0	$3,243	**$24,859**	$45
3	FEEDWATER & MISC. BOP SYSTEMS	$60,063	$0	$27,906	$0	$0	**$87,970**	$7,823	$0	$15,671	**$111,463**	$203
4	PC BOILER											
4.1	PC Boiler & Accessories	$211,626	$0	$120,584	$0	$0	**$332,210**	$31,973	$0	$36,418	**$400,601**	$728
4.2	SCR (w/4.1)	$0	$0	$0	$0	$0	**$0**	$0	$0	$0	**$0**	$0
4.3	Open	$0	$0	$0	$0	$0	**$0**	$0	$0	$0	**$0**	$0
4.4-4.9	Boiler BoP (w/ ID Fans)	$0	$0	$0	$0	$0	**$0**	$0	$0	$0	**$0**	$0
	SUBTOTAL 4	**$211,626**	**$0**	**$120,584**	**$0**	**$0**	**$332,210**	**$31,973**	**$0**	**$36,418**	**$400,601**	**$728**
5	FLUE GAS CLEANUP	$110,730	$0	$37,460	$0	$0	**$148,190**	$13,819	$0	$16,201	**$178,210**	$324
5B	CO2 REMOVAL & COMPRESSION	$157,345	$39,134	$73,522	$0	$0	**$270,001**	$24,763	$63,649	$71,683	**$430,096**	$782
6	COMBUSTION TURBINE/ACCESSORIES											
6.1	Combustion Turbine Generator	N/A	$0	N/A	$0	$0	**$0**	$0	$0	$0	**$0**	$0
6.2-6.9	Combustion Turbine Other	$0	$0	$0	$0	$0	**$0**	$0	$0	$0	**$0**	$0
	SUBTOTAL 6	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**
7	HRSG, DUCTING & STACK											
7.1	Heat Recovery Steam Generator	N/A	$0	N/A	$0	$0	**$0**	$0	$0	$0	**$0**	$0
7.2-7.9	HRSG Accessories, Ductwork and Stack	$21,167	$1,095	$14,159	$0	$0	**$36,421**	$3,248	$0	$5,212	**$44,880**	$82
	SUBTOTAL 7	**$21,167**	**$1,095**	**$14,159**	**$0**	**$0**	**$36,421**	**$3,248**	**$0**	**$5,212**	**$44,880**	**$82**
8	STEAM TURBINE GENERATOR											
8.1	Steam TG & Accessories	$71,502	$0	$8,797	$0	$0	**$80,298**	$7,049	$0	$8,735	**$96,082**	$175
8.2-8.9	Turbine Plant Auxiliaries and Steam Piping	$32,420	$1,340	$16,774	$0	$0	**$50,534**	$4,113	$0	$7,820	**$62,466**	$114
	SUBTOTAL 8	**$103,921**	**$1,340**	**$25,571**	**$0**	**$0**	**$130,832**	**$11,162**	**$0**	**$16,554**	**$158,548**	**$288**
9	COOLING WATER SYSTEM	$20,276	$10,185	$18,247	$0	$0	**$48,708**	$4,459	$0	$7,179	**$60,345**	$110
10	ASH/SPENT SORBENT HANDLING SYS	$6,168	$182	$8,009	$0	$0	**$14,360**	$1,336	$0	$1,614	**$17,310**	$31
11	ACCESSORY ELECTRIC PLANT	$32,248	$13,639	$36,031	$0	$0	**$81,918**	$7,034	$0	$11,133	**$100,085**	$182
12	INSTRUMENTATION & CONTROL	$11,217	$0	$11,250	$0	$0	**$22,466**	$1,984	$1,123	$3,152	**$28,726**	$52
13	IMPROVEMENTS TO SITE	$3,562	$2,048	$7,637	$0	$0	**$13,248**	$1,314	$0	$2,912	**$17,475**	$32
14	BUILDINGS & STRUCTURES	$0	$28,755	$27,278	$0	$0	**$56,034**	$4,949	$0	$9,147	**$70,130**	$128
	TOTAL COST	**$771,212**	**$105,188**	**$421,446**	**$0**	**$0**	**$1,297,846**	**$118,635**	**$69,515**	**$208,967**	**$1,694,964**	**$3,082**
	Owner's Costs											
	Preproduction Costs											
	6 Months All Labor										$11,413	
	1 Month Maintenance Materials										$1,352	
	1 Month Non-fuel Consumables										$2,157	
	1 Month Waste Disposal										$376	
	25% of 1 Months Fuel Cost at 100% CF							#VALUE!			$2,647	
	2% of TPC										$33,899	
	Total										**$51,844**	
	Inventory Capital											
	60 day supply of fuel & consumables at 100% CF										$27,809	
	0.5% of TPC (spare parts)										$8,475	
	Total										**$36,284**	
	Initial Cost for Catalyst and Chemicals										$14,027	
	Land										$900	
	Other Owner's Costs										$247,348	
	Financing Costs										$44,523	
	Total Overnight Costs (TOC)										**$2,089,890**	
	TASC Multiplier								(IOU, high-risk, 35 year)		1.14	
	Total As-Spent Cost (TASC)										**$2,391,595**	

Exhibit 6-5: Case-2B Total Plant Costs Summary

Acct No.	Item/Description	Equipment Cost	Material Cost	Labor Direct	Labor Indirect	Sales Tax	Bare Erected Cost $	Eng'g CM H.O.& Fee	Contingencies Process	Contingencies Project	TOTAL PLANT COST $	TOTAL PLANT COST $/kW
1	COAL & SORBENT HANDLING	$22,573	$5,749	$13,319	$0	$0	**$41,641**	$3,652	$0	$6,794	**$52,087**	$95
2	COAL & SORBENT PREP & FEED	$15,207	$850	$3,810	$0	$0	**$19,867**	$1,689	$0	$3,233	**$24,789**	$45
3	FEEDWATER & MISC. BOP SYSTEMS	$59,846	$0	$27,807	$0	$0	**$87,653**	$7,794	$0	$15,609	**$111,056**	$202
4	PC BOILER											
4.1	PC Boiler & Accessories	$210,979	$0	$120,215	$0	$0	**$331,195**	$31,875	$0	$36,307	**$399,377**	$726
4.2	SCR (w/4.1)	$0	$0	$0	$0	$0	**$0**	$0	$0	$0	**$0**	$0
4.3	Open	$0	$0	$0	$0	$0	**$0**	$0	$0	$0	**$0**	$0
4.4-4.9	Boiler BoP (w/ ID Fans)	$0	$0	$0	$0	$0	**$0**	$0	$0	$0	**$0**	$0
	SUBTOTAL 4	**$210,979**	**$0**	**$120,215**	**$0**	**$0**	**$331,195**	**$31,875**	**$0**	**$36,307**	**$399,377**	**$726**
5	FLUE GAS CLEANUP	$110,368	$0	$37,335	$0	$0	**$147,703**	$13,773	$0	$16,148	**$177,624**	$323
5B	CO2 REMOVAL & COMPRESSION	$147,884	$40,892	$77,478	$0	$0	**$266,255**	$24,421	$60,973	$70,330	**$421,978**	$767
6	COMBUSTION TURBINE/ACCESSORIES											
6.1	Combustion Turbine Generator	N/A	$0	N/A	$0	$0	**$0**	$0	$0	$0	**$0**	$0
6.2-6.9	Combustion Turbine Other	$0	$0	$0	$0	$0	**$0**	$0	$0	$0	**$0**	$0
	SUBTOTAL 6	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**
7	HRSG, DUCTING & STACK											
7.1	Heat Recovery Steam Generator	N/A	$0	N/A	$0	$0	**$0**	$0	$0	$0	**$0**	$0
7.2-7.9	HRSG Accessories, Ductwork and Stack	$21,163	$1,095	$14,156	$0	$0	**$36,414**	$3,247	$0	$5,211	**$44,873**	$82
	SUBTOTAL 7	**$21,163**	**$1,095**	**$14,156**	**$0**	**$0**	**$36,414**	**$3,247**	**$0**	**$5,211**	**$44,873**	**$82**
8	STEAM TURBINE GENERATOR											
8.1	Steam TG & Accessories	$70,955	$0	$8,720	$0	$0	**$79,676**	$6,995	$0	$8,667	**$95,338**	$173
8.2-8.9	Turbine Plant Auxiliaries and Steam Piping	$32,837	$1,327	$16,745	$0	$0	**$50,910**	$4,146	$0	$7,861	**$62,916**	$114
	SUBTOTAL 8	**$103,792**	**$1,327**	**$25,466**	**$0**	**$0**	**$130,585**	**$11,141**	**$0**	**$16,528**	**$158,254**	**$288**
9	COOLING WATER SYSTEM	$20,129	$10,122	$18,129	$0	$0	**$48,380**	$4,429	$0	$7,132	**$59,940**	$109
10	ASH/SPENT SORBENT HANDLING SYS	$6,152	$182	$7,987	$0	$0	**$14,321**	$1,332	$0	$1,610	**$17,263**	$31
11	ACCESSORY ELECTRIC PLANT	$31,009	$12,982	$34,328	$0	$0	**$78,319**	$6,725	$0	$10,635	**$95,679**	$174
12	INSTRUMENTATION & CONTROL	$11,190	$0	$11,222	$0	$0	**$22,412**	$1,979	$1,121	$3,145	**$28,656**	$52
13	IMPROVEMENTS TO SITE	$3,558	$2,045	$7,627	$0	$0	**$13,230**	$1,313	$0	$2,909	**$17,451**	$32
14	BUILDINGS & STRUCTURES	$0	$28,718	$27,247	$0	$0	**$55,966**	$4,943	$0	$9,136	**$70,045**	$127
	TOTAL COST	**$762,513**	**$104,822**	**$425,660**	**$0**	**$0**	**$1,292,995**	**$118,209**	**$62,778**	**$205,091**	**$1,679,074**	**$3,053**
	Owner's Costs											
	Preproduction Costs											
	6 Months All Labor										$11,341	
	1 Month Maintenance Materials										$1,340	
	1 Month Non-fuel Consumables										$2,140	
	1 Month Waste Disposal										$374	
	25% of 1 Months Fuel Cost at 100% CF										$2,635	
	2% of TPC										$33,581	
	Total										**$51,411**	
	Inventory Capital											
	60 day supply of fuel & consumables at 100% CF										$27,658	
	0.5% of TPC (spare parts)										$8,395	
	Total										**$36,053**	
	Initial Cost for Catalyst and Chemicals										$14,027	
	Land										$900	
	Other Owner's Costs										$244,773	
	Financing Costs										$44,059	
	Total Overnight Costs (TOC)										**$2,070,298**	
	TASC Multiplier								(IOU, high-risk, 35 year)		1.14	
	Total As-Spent Cost (TASC)										**$2,369,260**	

Exhibit 6-6: Case-1A Initial and Annual Operating and Maintenance Costs

INITIAL & ANNUAL O&M EXPENSES		
Case 1A	Cost Base (Jun):	2011
	Heat Rate-net (Btu/kWh):	10,918
	MWe-net:	550
	Capacity Factor (%):	85

OPERATING & MAINTENANCE LABOR

Operating Labor			
Operating Labor Rate (base):	39.70	$/hour	
Operating Labor Burden:	30.00	% of base	
Labor O-H Charge Rate:	25.00	% of labor	
			Total
Skilled Operator	2.0		2.0
Operator	11.3		11.3
Foreman	1.0		1.0
Lab Tech's, etc.	2.0		2.0
TOTAL-O.J.'s	16.3		16.3

	Annual Cost $	Annual Unit Cost $/kW-net
Annual Operating Labor Cost	$7,384,208	$13.426
Maintenance Labor Cost	$12,074,559	$21.953
Administrative & Support Labor	$5,101,661	$9.276
Property Taxes and Insurance	$37,775,525	$68.682
TOTAL FIXED OPERATING COSTS	**$62,335,953**	**$113.336**

VARIABLE OPERATING COSTS

						$/kWh-net
Maintenance Material Cost					**$18,051,025**	**$0.00441**
Consumables	Consumption Initial Fill	Consumption /Day	Unit Cost	Initial Fill Cost		
Water(/1000 gallons)	0	6,809	1.67	**$0**	**$3,536,201**	**$0.00086**
Chemicals						
MU & WT Chem.(lbs)	0	30,009	0.27	$0	$2,493,665	$0.00061
Limestone (ton)	0	622	33.48	$0	$6,459,044	$0.00158
Carbon (Mercury Removal) lb	0	0	1.63	$0	$0	$0.00000
Solvent (ton)	2,300	0.42	4,000.00	$9,200,000	$524,712	$0.00013
NaOH (tons)	0	0.00	671.16	$0	$0	$0.00000
H2SO4 (tons)	0	0.00	214.78	$0	$0	$0.00000
Corrosion Inhibitor	0	0	0.00	$126,041	$0	$0.00000
Activated Carbon (lb)	0	1,761	1.63	$0	$887,741	$0.00022
Ammonia (19% NH3) ton	0	92	330.00	$0	$9,461,389	$0.00231
Subtotal Chemicals				**$9,326,041**	**$19,826,552**	**$0.00484**
Other						
Supplemental Fuel (MBtu)	0	0	0.00	$0	$0	$0.00000
SCR Catalyst (m3)	w/equip.	0.39	8,938.80	$0	$1,077,080	$0.00026
Biocatalyst	N/A	N/A	1.00	$4,827,395	$2,926,457	$0.00071
Emission Penalties	0	0	0.00	$0	$0	$0.00000
Subtotal Other				**$4,827,395**	**$4,003,537**	**$0.00098**
Waste Disposal						
Fly Ash (ton)	0	479	25.11	$0	$3,732,849	$0.00091
Bottom Ash (ton)	0	120	25.11	$0	$933,213	$0.00023
Subtotal-Waste Disposal				**$0**	**$4,666,062**	**$0.00114**
By-products & Emissions						
Gypsum (tons)	0	966	0.00	$0	$0	$0.00000
Subtotal By-Products				**$0**	**$0**	**$0.00000**
TOTAL VARIABLE OPERATING COSTS				**$14,153,436**	**$50,083,378**	**$0.01223**
Fuel (ton)	0	6,177	68.60	$0	**$131,459,980**	**$0.03208**

Exhibit 6-7: Case-2A Initial and Annual Operating and Maintenance Costs

INITIAL & ANNUAL O&M EXPENSES		
Case 2A	Cost Base (Jun):	2011
	Heat Rate-net (Btu/kWh):	10,553
	MWe-net:	550
	Capacity Factor (%):	85

OPERATING & MAINTENANCE LABOR

Operating Labor

Operating Labor Rate (base):	39.70	$/hour
Operating Labor Burden:	30.00	% of base
Labor O-H Charge Rate:	25.00	% of labor

		Total
Skilled Operator	2.0	2.0
Operator	11.3	11.3
Foreman	1.0	1.0
Lab Tech's, etc.	2.0	2.0
TOTAL-O.J.'s	16.3	16.3

	Annual Cost $	Annual Unit Cost $/kW-net
Annual Operating Labor Cost	$7,384,208	$13.426
Maintenance Labor Cost	$10,855,276	$19.737
Administrative & Support Labor	$4,586,498	$8.339
Property Taxes and Insurance	$33,960,971	$61.746
TOTAL FIXED OPERATING COSTS	**$56,786,953**	**$103.247**

VARIABLE OPERATING COSTS

		$/kWh-net
Maintenance Material Cost	**$16,228,242**	**$0.00396**

Consumables	Consumption Initial Fill	Consumption /Day	Unit Cost	Initial Fill Cost		
Water(/1000 gallons)	0	6,596	1.67	**$0**	**$3,425,755**	**$0.00084**
Chemicals						
MU & WT Chem.(lbs)	0	28,176	0.27	$0	$2,341,305	$0.00057
Limestone (ton)	0	600	33.48	$0	$6,231,238	$0.00152
Carbon (Mercury Removal) lb	0	0	1.63	$0	$0	$0.00000
Solvent (ton)	2,300	0.08	4,000.00	$9,200,000	$100,790	$0.00002
NaOH (tons)	0	5.44	671.16	$0	$1,133,008	$0.00028
H2SO4 (tons)	0	0.00	214.78	$0	$0	$0.00000
Corrosion Inhibitor	0	0	0.00	$126,041	$0	$0.00000
Activated Carbon (lb)	0	1,603	1.63	$0	$808,372	$0.00020
Ammonia (19% NH3) ton	0	89	330.00	$0	$9,145,080	$0.00223
Subtotal Chemicals				**$9,326,041**	**$19,759,793**	**$0.00482**
Other						
Supplemental Fuel (MBtu)	0	0	0.00	$0	$0	$0.00000
SCR Catalyst (m3)	w/equip.	0.38	8,938.80	$0	$1,041,091	$0.00025
Biocatalyst	N/A	N/A	1.00	$4,827,395	$1,653,199	$0.00040
Emission Penalties	0	0	0.00	$0	$0	$0.00000
Subtotal Other				**$4,827,395**	**$2,694,289**	**$0.00066**
Waste Disposal						
Fly Ash (ton)	0	463	25.11	$0	$3,608,054	$0.00088
Bottom Ash (ton)	0	116	25.11	$0	$902,014	$0.00022
Subtotal-Waste Disposal				**$0**	**$4,510,068**	**$0.00110**
By-products & Emissions						
Gypsum (tons)	0	951	0.00	$0	$0	$0.00000
Subtotal By-Products				**$0**	**$0**	**$0.00000**
TOTAL VARIABLE OPERATING COSTS				**$14,153,436**	**$46,618,147**	**$0.01138**
Fuel (ton)	0	5,970	68.60	$0	**$127,065,064**	**$0.03101**

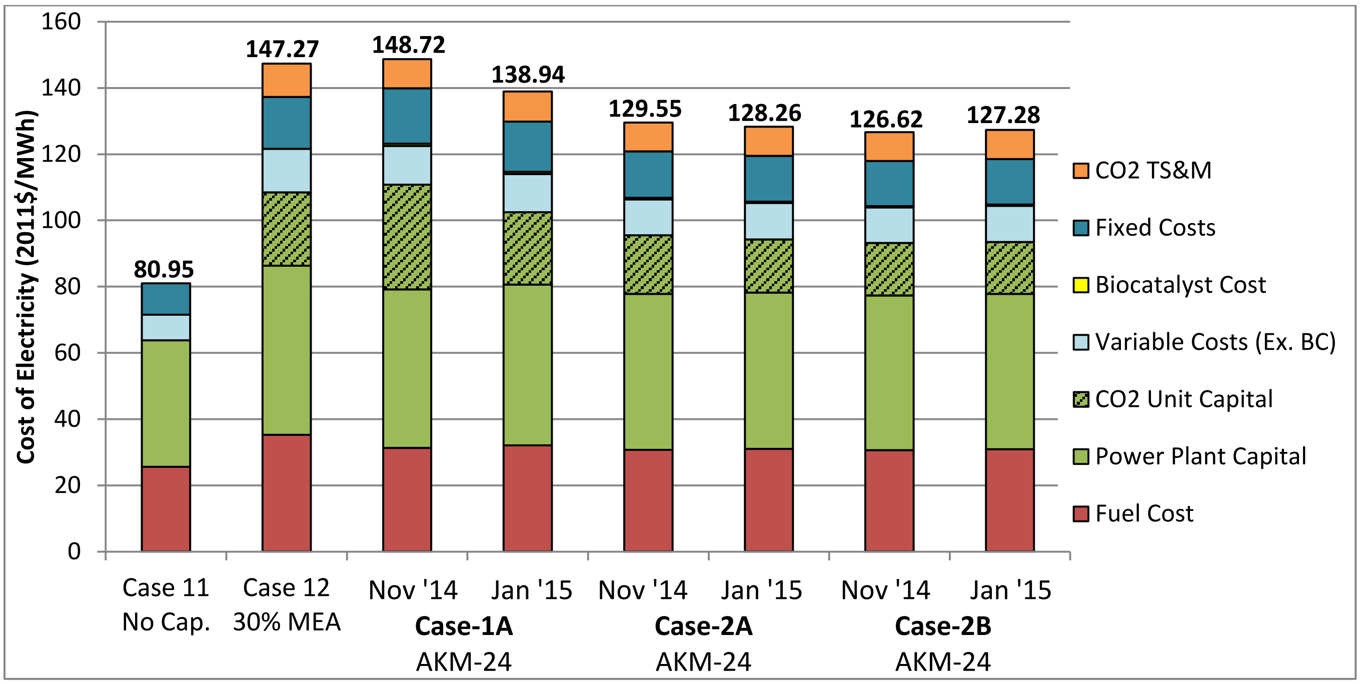
Exhibit 6-8: Case-2B Initial and Annual Operating and Maintenance Costs

INITIAL & ANNUAL O&M EXPENSES						Cost Base (Jun):	2011
Case 2B						Heat Rate-net (Btu/kWh):	10,506
						MWe-net:	550
						Capacity Factor (%):	85
OPERATING & MAINTENANCE LABOR							
Operating Labor							
Operating Labor Rate (base):	39.70	$/hour					
Operating Labor Burden:	30.00	% of base					
Labor O-H Charge Rate:	25.00	% of labor					
			Total				
Skilled Operator	2.0		2.0				
Operator	11.3		11.3				
Foreman	1.0		1.0				
Lab Tech's, etc.	2.0		2.0				
TOTAL-O.J.'s	16.3		16.3				
						Annual Cost	Annual Unit Cost
						$	$/kW-net
Annual Operating Labor Cost						$7,384,208	$13.426
Maintenance Labor Cost						$10,753,509	$19.551
Administrative & Support Labor						$4,543,500	$8.261
Property Taxes and Insurance						$33,642,589	$61.167
TOTAL FIXED OPERATING COSTS						**$56,323,806**	**$102.405**
VARIABLE OPERATING COSTS							
							$/kWh-net
Maintenance Material Cost						**$16,076,103**	**$0.00393**
Consumables	Consumption		Unit	Initial Fill			
	Initial Fill	/Day	Cost	Cost			
Water(/1000 gallons)	0	6,614	1.67	**$0**		**$3,435,105**	**$0.00084**
Chemicals							
MU & WT Chem.(lbs)	0	27,938	0.27	$0		$2,321,539	$0.00057
Limestone (ton)	0	597	33.48	$0		$6,201,684	$0.00151
Carbon (Mercury Removal) lb	0	0	1.63	$0		$0	$0.00000
Solvent (ton)	2,300	0.08	4,000.00	$9,200,000		$94,706	$0.00002
NaOH (tons)	0	5.45	671.16	$0		$1,134,404	$0.00028
H2SO4 (tons)	0	0.00	214.78	$0		$0	$0.00000
Corrosion Inhibitor	0	0	0.00	$126,041		$0	$0.00000
Activated Carbon (lb)	0	1,605	1.63	$0		$809,369	$0.00020
Ammonia (19% NH3) ton	0	89	330.00	$0		$9,104,045	$0.00222
Subtotal Chemicals				**$9,326,041**		**$19,665,747**	**$0.00480**
Other							
Supplemental Fuel (MBtu)	0	0	0.00	$0		$0	$0.00000
SCR Catalyst (m3)	w/equip.	0.37	8,938.80	$0		$1,036,422	$0.00025
Biocatalyst	N/A	N/A	1.00	$4,827,395		$1,544,540	$0.00038
Emission Penalties	0	0	0.00	$0		$0	$0.00000
Subtotal Other				**$4,827,395**		**$2,580,962**	**$0.00063**
Waste Disposal							
Fly Ash (ton)	0	461	25.11	$0		$3,591,864	$0.00088
Bottom Ash (ton)	0	115	25.11	$0		$897,967	$0.00022
Subtotal-Waste Disposal				**$0**		**$4,489,831**	**$0.00110**
By-products & Emissions							
Gypsum (tons)	0	951	0.00	$0		$0	$0.00000
Subtotal By-Products				**$0**		**$0**	**$0.00000**
TOTAL VARIABLE OPERATING COSTS				**$14,153,436**		**$46,247,747**	**$0.01129**
Fuel (ton)	0	5,943	68.60	$0		**$126,494,903**	**$0.03087**

7. COST OF ELECTRICITY ANALYSIS

The Cost of Electricity (COE) analysis methodology is based on Section 2.7.4 of the BBS report [2], with updates presented in reference [3]. The resulting COE for the AKM-24 cases with updated CO_2 compression analysis (revision Jan '15) and original basis (revision Nov '14) is compared to BBS Cases 11 and 12 in Exhibit 7-1. The AKM-24 Case-2B provides the lowest COE of the cases evaluated in this study and is 56 percent greater than the generation with no CO_2 capture, Case 11 in Exhibit 7-1. This compares to the 82 percent increase in COE with the amine-based CO_2 capture, BBS Case 12.

Exhibit 7-1: COE for BBS Cases 11 and 12 and AKM 24 Cases



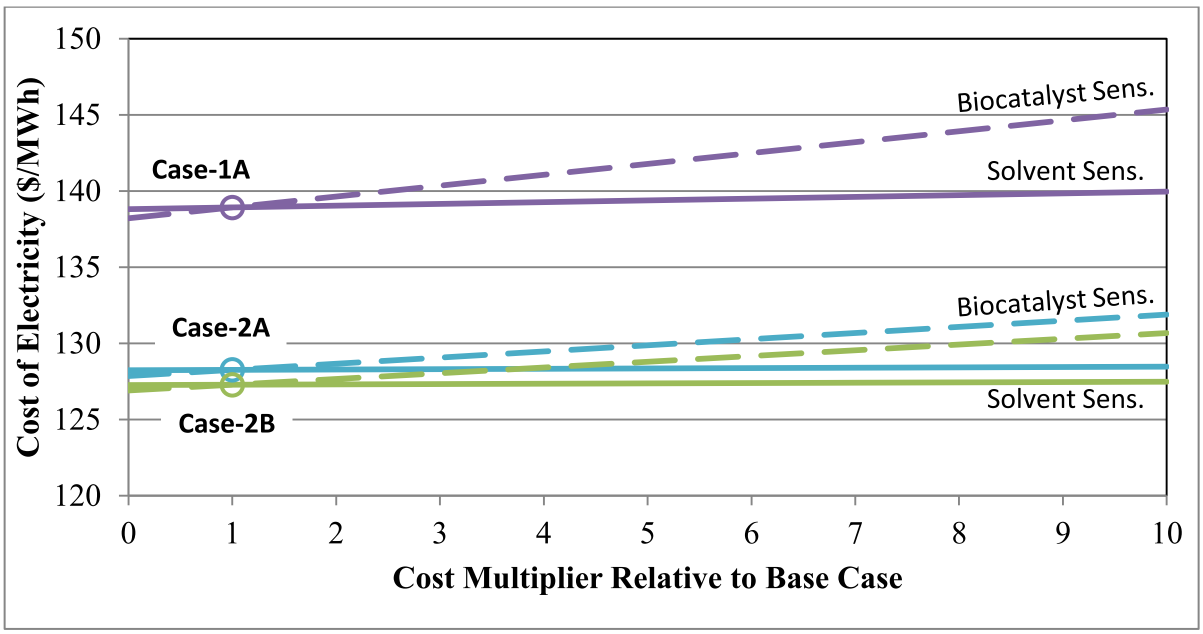
COE (2011$/MWh)	Case 11 No Cap.	Case 12 MEA	Case-1A Nov '14	Case-1A Jan '15	Case-2A Nov '14	Case-2A Jan '15	Case-2B Nov '14	Case-2B Jan '15
Fuel Cost	25.5	35.3	31.3	32.1	30.7	31.0	30.6	30.9
Power Plant Cap.	38.2	51.0	47.9	48.5	47.1	47.2	46.7	46.9
CO_2 Unit Capital	0.00	22.1	31.6	21.8	17.7	16.0	15.9	15.7
Variable Costs	7.74	13.2	11.7	11.5	10.9	11.0	10.7	10.9
Biocatalyst Cost	0.00	0.00	0.70	0.71	0.40	0.40	0.37	0.38
Fixed Costs	9.48	15.7	16.7	15.2	14.1	13.9	13.7	13.7
CO_2 TS&M	0.00	9.99	8.86	9.09	8.69	8.78	8.65	8.74
Total COE	**80.96**	**147.27**	**148.72**	**138.94**	**129.54**	**128.26**	**126.62**	**127.28**

8. SENSITIVITY STUDIES

Akermin performed sensitivity studies to quantify the impact on COE for technology specific parameters including solvent cost, biocatalyst cost (or half-life), and biocatalyst recovery system cost. These sensitivity studies are based on the updated capital costs and power requirements for vacuum blowers and CO_2 compressors per the vendor quote (MAN Diesel & Turbo Dec 2014). In addition, WorleyParsons also performed sensitivity studies for the critical power plant parameters of capacity factor and fuel cost. These sensitivity studies have been updated by Akermin implementing updated cost and energy data from MAN Turbo.

The sensitivity of COE to solvent cost and biocatalyst cost is shown in Exhibit 8-1 for the AKM24 cases. The reference unit cost for AKM-24 (as pure salt) is $4/kg and for the biocatalyst the unit cost is undisclosed. Solvent and biocatalyst cost were varied from 0% to 1000% of the reference cost for this study.

Exhibit 8-1: Sensitivity of COE to Solvent & Biocatalyst Replacement Rate & Cost

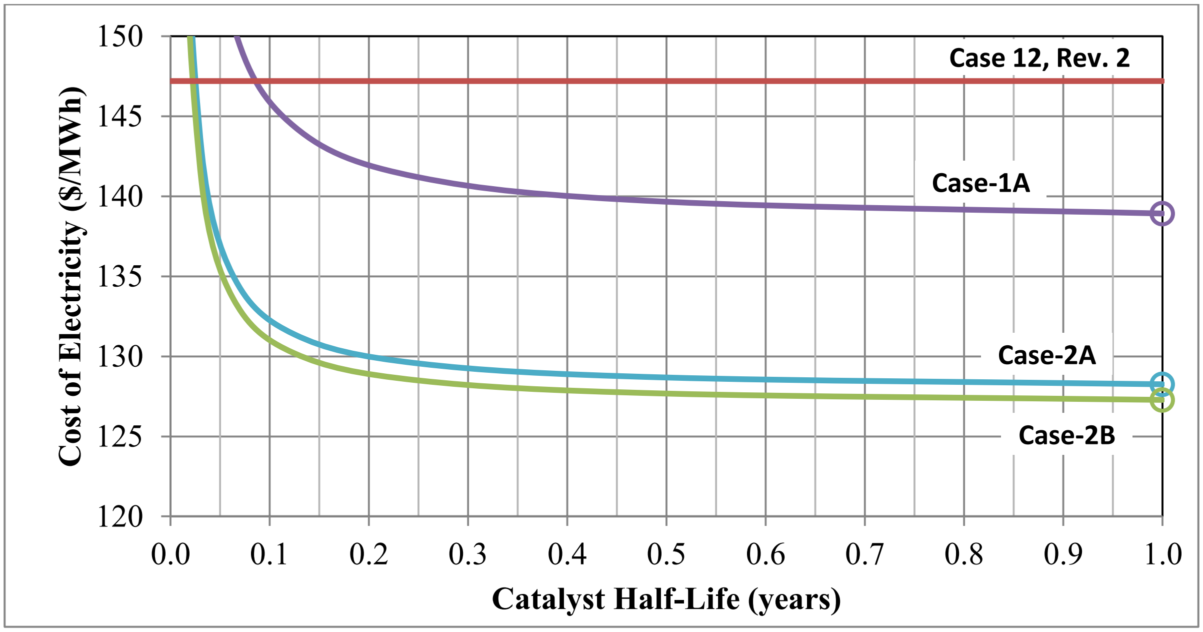


Results show that the COE is not very sensitive to solvent cost. For example, even if the solvent cost is ten times the reference value for this study, the COE changes by as little as 1%. The reason for this is that there is relatively low solvent loss when using a non-volatile salt as the capture agent. The only solvent loss is related to build up of heat stable salts, proportional to SOx and NOx slip from upstream gas conditioning systems.

A sensitivity study was also performed to understand the impact of varied biocatalyst cost on total COE. Results show that if biocatalyst were to cost ten times the value assumed in the AKM24 reference cases, then the total COE would increase by 4% to 5%, depending on the case. The biocatalyst consumption rate is higher for Case-1A than for Case-2B because of a higher circulation rate in that case, which results in higher liquid volume estimate. It is notable that this conclusion is the same for a 10-fold increase in replacement rate, which results in a 4% to 5% increase in COE.

The biocatalyst consumption rate can be correlated to its half-life, which is assumed to be one-year for all Akermin cases in this TEA. However, it is instructive to explore the impact on COE for varied biocatalyst half-life; results for half-life sensitivity are shown in Exhibit 8-2. The results show that the change in COE is relatively small, for example less than ~$1 per MWh if the half-life is reduced from one year to half a year. However, if the half-life drops below about one month, then the COE begins to approach the NETL Case-12 benchmark.

Exhibit 8-2: Sensitivity of COE to Biocatalyst Half-life



Finally, a sensitivity study was performed that varied the capital cost of the biocatalyst recovery system (BRS) relative reference values assumed for Case-2B. The BRS in Case 2B has a bare erected cost of $22 MM. The CO_2 capture unit's bare erected cost with varied BRS cost is presented in Exhibit 8-3. The resulting impact on total COE is also presented in Exhibit 8-4. Results show that if the biocatalyst recovery system had 10-fold higher capital cost, then the total COE is about 13% higher. Notably, the Case-2B reference condition achieves the BEC cost targets defined for this project (i.e., 20% savings relative to NETL-12).

Exhibit 8-3: Sensitivity of BEC to Biocatalyst Recovery Cost

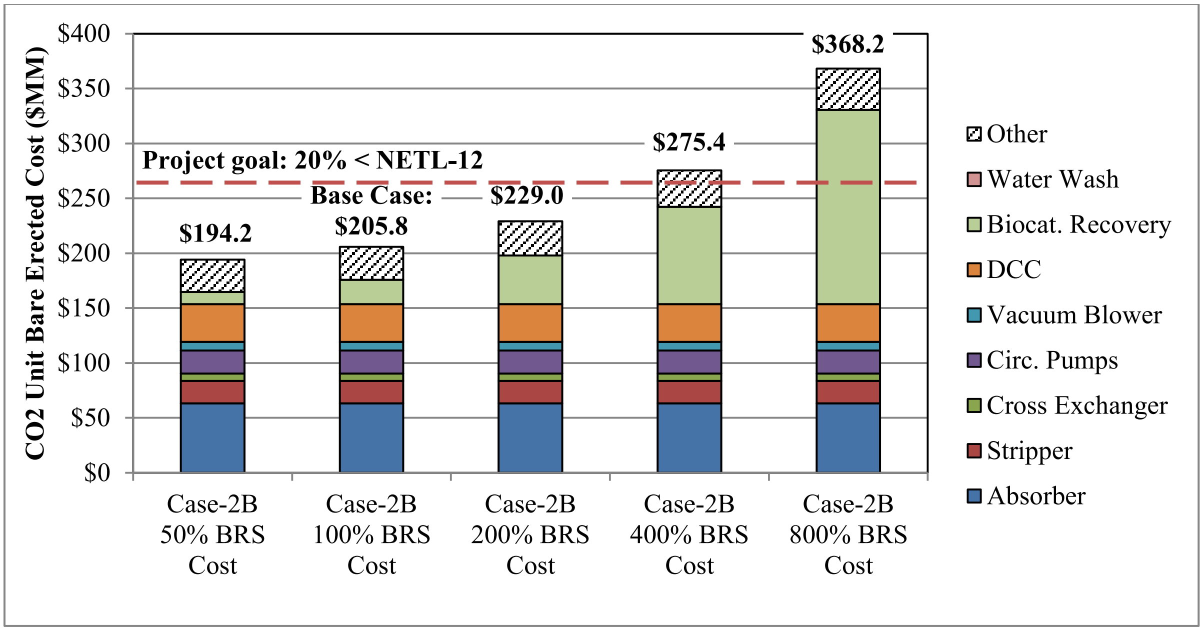
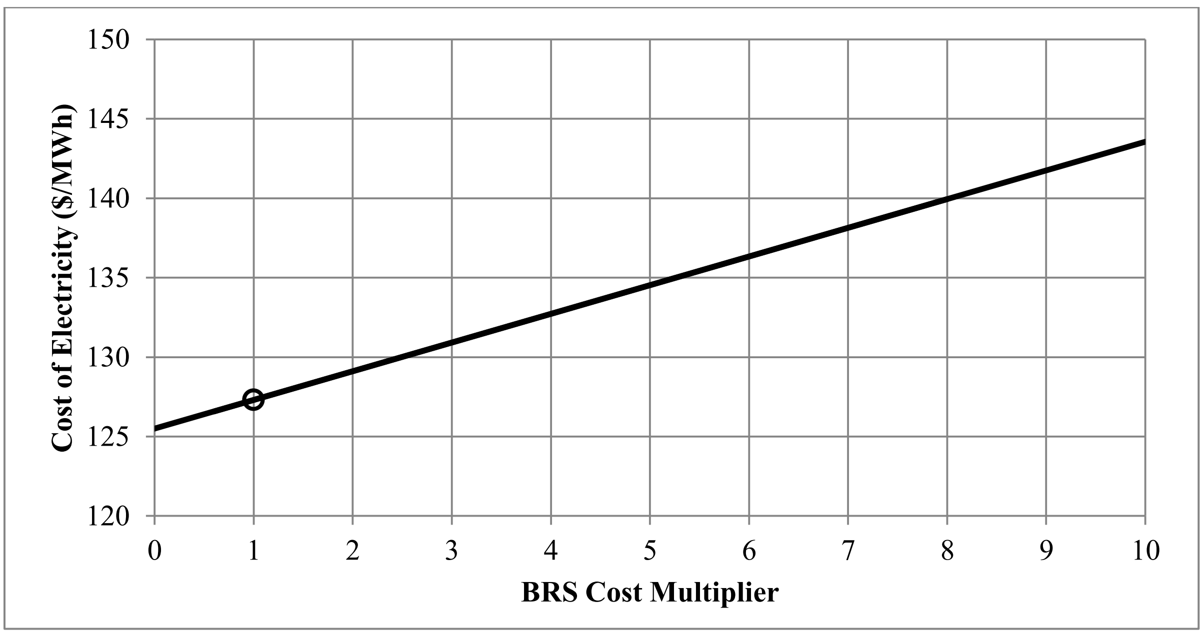
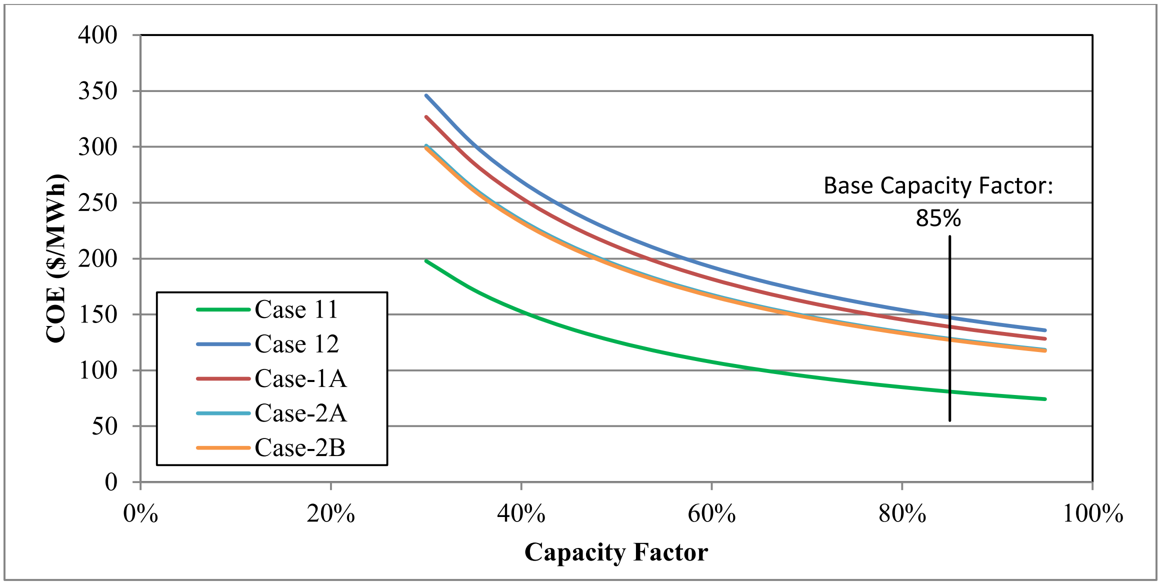


Exhibit 8-4: Sensitivity of COE to Biocatalyst Recovery Equipment Cost



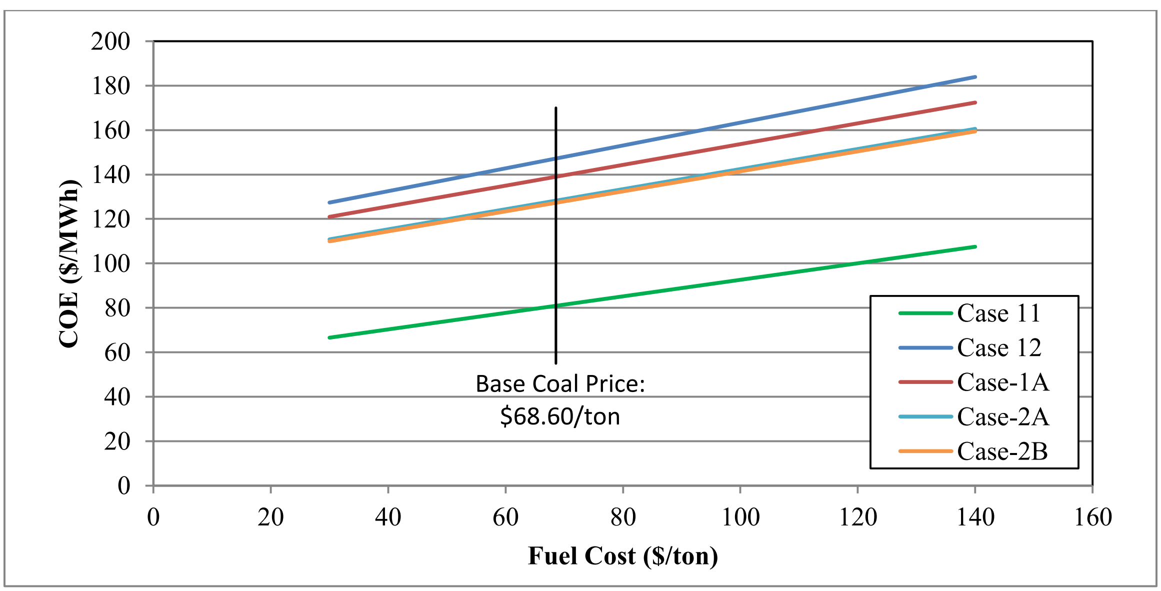
A sensitivity study was also performed relative to the capacity factor. The COE sensitivity to capacity factor for the BBS Cases and the AKM-24 Cases are shown in Exhibit 8-5. The capacity factors in this analysis vary from 30 to 90 percent and the figure is used to determine how varying this parameter would impact the economic viability of each technical option. The variation in capacity factor can be a result of how a facility is dispatched or unplanned outages related to the reliability of a technology. With the assumption that all technologies will have the same capacity factor, there is no change in the economic ordering of the technologies.

Exhibit 8-5: Sensitivity of COE to Capacity Factor



Sensitivity studies were also performed to determine if a change in fuel cost would favor one of the cases over another, or significantly change the results with respect to the reference cases. In this investigation, the fuel costs were varied from 50 to 200% of the reference cost of $68.60/ton, or a fuel cost range from $34.30/ton to $137.20/ton. Exhibit 8-6 presents the dependence of the COE on fuel cost for cases with updated CO_2 compression costs. The COE of the AKM-24 cases show a similar dependence on fuel costs relative to Case 11 and Case 12. In addition, the case order of preferred economics remained constant for all fuel costs.

Exhibit 8-6: Sensitivity of COE to Coal Price



9. COMPARISON TO PREVIOUS RESULTS

Exhibit 9-1 below presents the COE, % Increased COE, cost of CO_2 capture, and cost of CO_2 avoided for Preliminary TEA study results before CO_2 compression cost and energy updates (Nov. 2014) and after (Jan. 2015). The calculation uses a common methodology for all the cases with consistent technical and economic assumptions for the BBS reference as well as the AKM24 cases with the exception of process contingency. A process contingency of 30% was applied to the AKM24 CO_2 capture system capital costs, while a 20% process contingency was applied to the post-combustion CO_2 capture system capital costs in BBS Case 12. More detailed results for the Nov. 2014 revision may be found in Appendix 3.

The key finding is that the Jan 2015 results indicate potential to reduce COE and cost of capture for Case-1A by 6.5% and 16.2%, respectively. There was relatively minor change for Case-2A and Case-2B between the Jan 2015 and Nov 2014 revisions. The final conclusion remains: Case-2B provides the best economics of all cases studied with Case-2A having similar economics but further requiring technological development.

Exhibit 9-1: Comparison of Key Metrics to Previous Results

	BBS Case 12	**AKM24 Case 1A**	**AKM24 Case 2A**	**AKM24 Case 2B**
Original Revision, Nov. 2014				
Cost of Electricity, 2011$/MWh	$147.27	$148.72	$129.55	$126.62
% Increased COE	82%	83.70%	60.00%	56.4%
Cost of CO_2 Captured, 2011$/tonne CO_2	$66.47	$76.62	$55.97	$52.87
Cost of CO_2 Avoided, 2011$/tonne CO_2	$95.98	$96.32	$68.90	$64.70
Updated Revision, Jan. 2015				
Cost of Electricity, 2011$/MWh	$147.27	$139.02	$128.28	$127.30
% Increased COE	82%	71.80%	58.50%	57.30%
Cost of CO_2 Captured, 2011$/tonne CO_2	$66.47	$64.20	$54.06	$53.01
Cost of CO_2 Avoided, 2011$/tonne CO_2	$95.98	$82.76	$67.15	$65.76

10. CONCLUSIONS & FUTURE WORK

The performance and cost results of AKM-24 design cases in comparison to BBS Cases 11 and 12 are summarized in Exhibit 10-1.

Exhibit 10-1: Performance and Cost Results, Rev. Jan 2015

	BBS Case 11	BBS Case 12	AKM-24 Case-1A	AKM-24 Case-2A	AKM-24 Case-2B
Gross Power Output, kWe	580,400	662,800	694,166	662,785	649,872
Auxiliary Power Requirements, kWe	30,410	112,830	144,166	112,785	99,872
Net Power Output, kWe	549,990	549,970	550,000	550,000	550,000
HHV Thermal Input, kWth	1,400,162	1,934,519	1,759,861	1,701,026	1,693,393
Net Plant HHV Efficiency, %	39.28%	28.43%	31.25%	32.33%	32.48%
Raw Water Withdrawal, gpm/MW net	9.7	18.3	15.4	14.7	14.7
Raw Water Withdrawal, m^3/MWh net	2.2	4.2	4.3	3.4	3.3
Raw Water Consumption, gpm/MW net	7.7	14.1	11.8	11.4	11.2
Raw Water Consumption, m^3/MWh net	1.7	3.2	3.3	2.6	2.5
CO_2 Generated, lb/h (Note)	957,272	1,322,604	1,202,394	1,162,195	1,156,981
CO_2 Generated, kg/h (Note)	434,218	599,933	545,406	527,172	524,807
Capture Efficiency		91.40%	91.20%	91.30%	91.70%
CO_2 Emitted, lb/h	957,272	113,446	105,999	100,584	95,667
CO_2 Emitted, kg/h	434,218	51,459	48,082	45,625	43,394
CO_2 Emissions, lb/MWh gross	1649	171	156.9	153.5	148.5
CO_2 Emissions, kg/MWh gross	748	78	70.8	69.7	67.7
CO_2 Emissions, lb/MWh net	1741	206	192.8	182.8	173.8
CO_2 Emissions, kg/MWh net	790	94	87.2	82.8	78.8
Total As-spent Capital, 2011$ x 1000	$1,529,135	$2,752,796	$2,659,199	$2,391,595	$2,369,260
Total As-spent Capital, 2011$/kW net	$2,780	$5,005	$4,835	$4,348	$4,308
Cost of Electricity, 2011$/MWh	$80.95	$147.27	$138.94	$128.26	$127.28
Levelized Cost of Electricity, 2011$/MWh	$102.65	$186.74	$176.30	$162.75	$161.51
% Increase in COE		82%	71.66%	58.46%	57.26%
Cost of CO_2 Captured, 2011$/tonne CO_2		$66.47	$64.20	$54.06	$53.01
Cost of CO_2 Avoided, 2011$/tonne CO_2		$95.98	$82.76	$67.15	$65.76

Note: Based on assumed 100% carbon conversion.

The major findings of this preliminary TEA are as follows:

1) Akermin Case 2B achieved the best economic performance of all cases.
2) Case-2B achieved 15.7% savings in gross power penalty relative to NETL Case-12.
3) Case 2B reduced the efficiency penalty from 10.9 (Case 12) to 6.8 percentage points.
4) Case 2B achieved 37% savings in Bare Erected Costs (BEC) for the CO_2 capture unit, (including vacuum blower but excluding CO2 compressor).
5) Case 2B achieved approximately 29% lower capital cost penalty (TASC basis) for the CO_2 capture unit relative to Case-12, including CO_2 compression.
6) Case-2B achieved 30% lower electricity cost penalty compared to NETL Case-12.
7) 57% ICOE achieved in Case-2B relative to no capture (NETL Case 11), notably better than the 82% ICOE for Case-12 but short of the long-term DOE goal of 35% ICOE.
8) Case 2B achieved 31% lower avoided cost of capture and 20% lower cost of capture.
9) Case 2B includes equipment and energy costs for the biocatalyst recovery system; sensitivity study reals the importance of this technology selection.
10) All AKM24 cases are relatively insensitive to solvent cost, because loss rate are assumed to be quite low with the non-volatile salt system.
11) The study assumes that the target of 12-months (1 year) can be achieved, where biocatalyst cost contribution to COE is relatively minor.

10.1 Recommendations for Evaluation Analysis in Final Report

Equipment configurations for integration of CO_2 capture system with the power plant equipment are similar to that of the BBS (NETL Case 12). Several alternative integration options that take into account specifics of the AKM-24 CO_2 capture system are potentially possible, and may improve overall plant performance (for example, considering heat recovery and integration). While these alternative configurations have not been evaluated in this preliminary TEA, they are recommended for assessment in the final TEA.

10.1.1 Vacuum Blowers vs. Multistage Compressors

In this preliminary TEA report, vacuum blowers are utilized to maintain vacuum in the AKM-24 desorption systems for Cases 1A and 2A, which operate at 0.16 bara (60°C) and 0.40 bara (80°C), respectively. Based on input from Man Turbo, the blower manufacturer, type AV multistage axial compressors, constructed with adjustable stator blades, were recommended for the vacuum service in the AKM24 desorption system [6]. Five AV units operating in parallel are required to satisfy Case-1A volumetric flow requirements, and two AV units are required for

Case-2A. Previous work suggested a different vacuum blower model where multiple units operating in parallel were required (Case 1A- 28 units, Case 2A – 8 units) to satisfy volumetric flow requirements, which resulted in complex and costly inlet/outlet arrangements. Future work will continue to investigate the vacuum blower and CO_2 compression equipment that best balances energy requirements and BEC, both critical parameters in the TEA.

10.1.2 Inter-stage Cooling

The AKM-24 cases, similar to BBS Case 12, do not include heat recovery on the CO_2 compressor inter-stage cooling, i.e. all heat is rejected to the cooling water. Steam cycle condensate could be used to replace cooling water, which saves water and improves net plant efficiency. A slipstream of the cold condensate exiting the condensate pump can be routed to the intercoolers in the CO_2 compression area. The condensate would serve as a heat sink for the heat generated by the CO_2 compressor. Heated condensate is sent back to the steam cycle's deaerator. Low pressure extractions from the steam turbine are thus reduced and steam turbine gross generation increased. Per the BBS report, the configuration with the heat recovery on the inter-stage cooling could have improved overall cycle efficiency for Case 12 by approximately 0.3 percentage points. Since the reboilers for the AKM24 cases operate at lower temperatures relative to NETL Case-12, there is a potential for additional heat recovery benefit in these systems. Thus, overall cycle efficiency improvements could be gained especially for Cases 1A and 2A where vacuum blowers are included in the process.

10.1.3 Equipment MOC

The absorption and desorption columns in the AKM-24 cases are carbon steel with stainless steel liners. Future work will examine the potential to reduce BEC by utilizing alternative MOC for these columns, using best available technology (such as concrete columns). The MOC for other equipment will also be examined, making appropriate recommendations with available market materials.

11. REFERENCES

1 DE-FE0012862, SOPO Appendix B – Basis for Techno-Economic Analysis.

2 Cost and Performance Baseline for Fossil Energy Plants, Volume 1: Bituminous Coal and Natural Gas to Electricity, Revision 2, November 2010, DOE/NETL-2010/1397, http://www.netl.doe.gov/research/energy-analysis/energy-baseline-studies

3 Updated Costs (June 2011 Basis) for Selected Bituminous Baseline Cases, August 2012, DOE/NETL-341/082312, http://www.netl.doe.gov/File%20Library/Research/Energy%20Analysis/Publications/BaselineCostUpdate.pdf

4 Quality Guidelines for Energy System Studies, CO_2 Impurity Design Parameters, August 2013, DOE/NETL-341/011212, http://www.netl.doe.gov/research/energy-analysis/quality-guidelines-qgess

5 MAN Diesel & Turbo Proposal # 7314-095.1, August 2014

6 Centrifugal and Axial Compressor Data sheet (API 617-7H), MAN Diesel & Turbo Job No. 7514102.75, December 3, 2014.

Appendix 1: SCPC Power Plant HMB, Rev. Nov 2014

Exhibit A1-1: Case-1A HMB Diagram, Power Plant

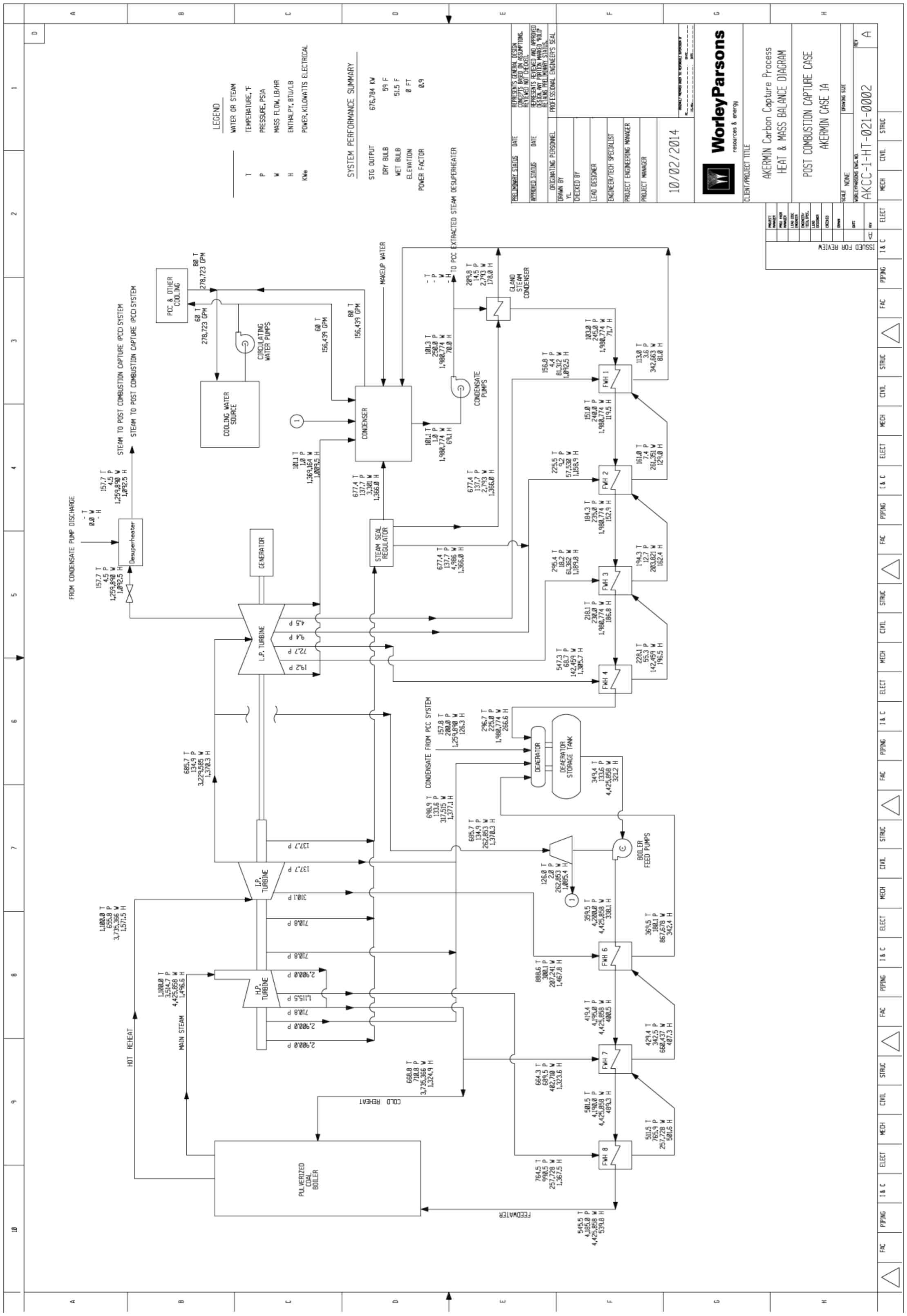


Exhibit A1-2: Case-2A HMB Diagram, Power Plant

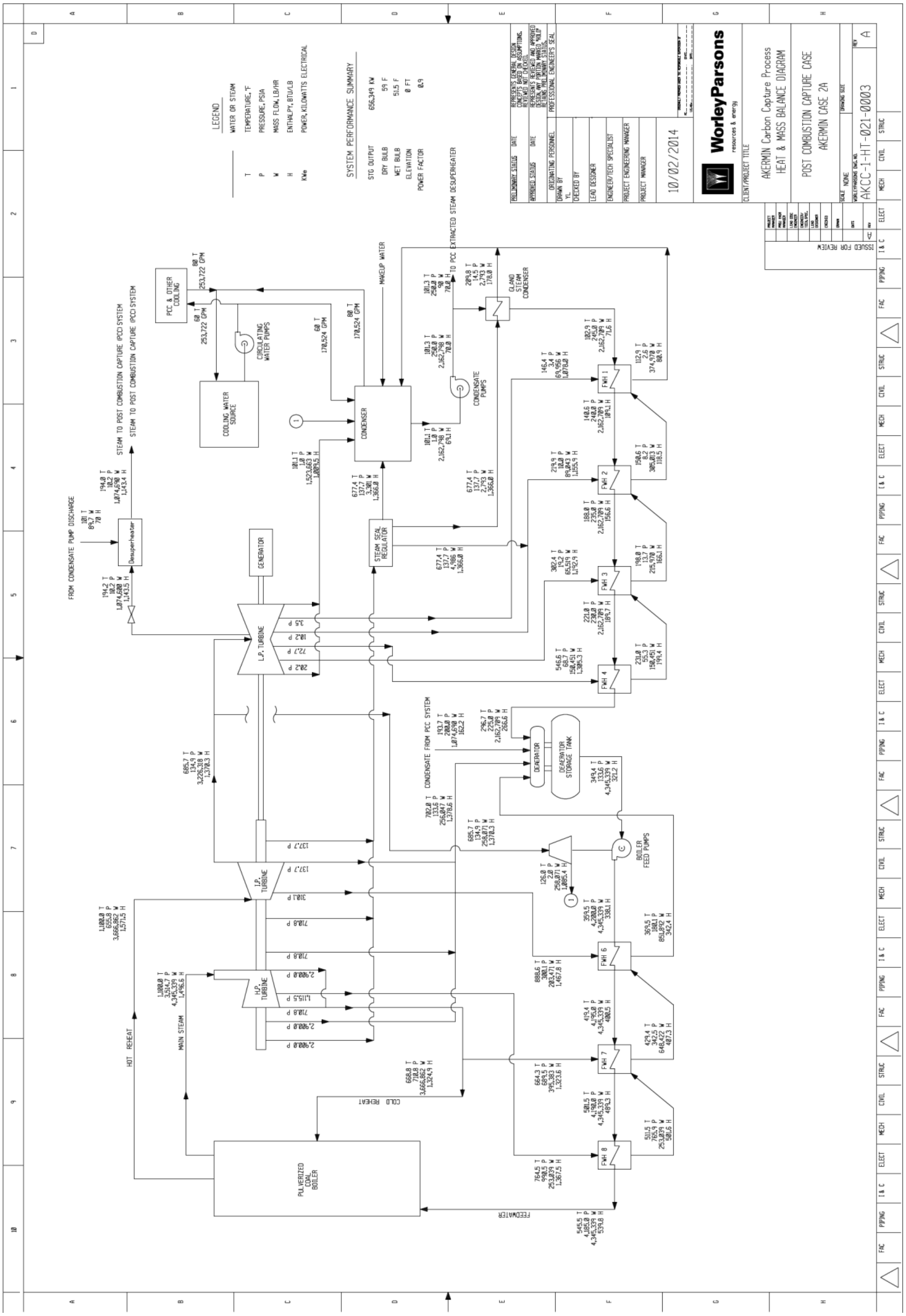
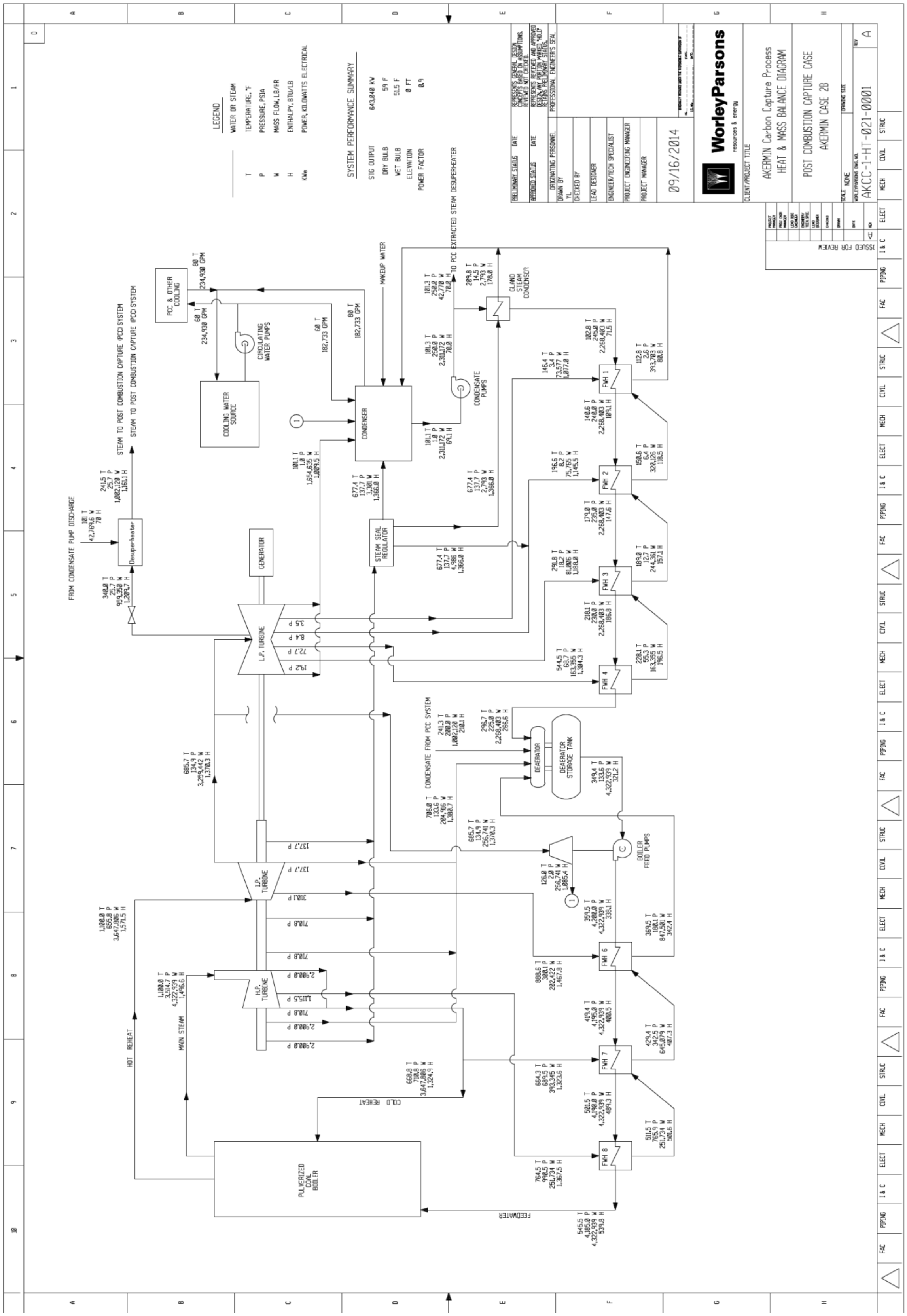


Exhibit A1-3: Case-2B HMB Diagram, Power Plant



Appendix 2: SCPC Power Plant Major Equipment Lists, Rev. Nov 2014

Major equipment lists for the SCPC plant designs equipped with AKM-24 CO_2 capture system are shown in the following tables. The accounts scope and numbers, and design assumptions used in the equipment lists are consistent with the BBS report Case 12.

A2.1: Case 1A-Major Equipment List

Account 1 - Fuel and Sorbent Handling

Item	Description	Type	Design Condition	Op. Qty.	Spares
1	Bottom Trestle Dumper and Receiving Hoppers	N/A	181 tonne (200 ton)	2	0
2	Feeder	Belt	572 tonne/h (630 tph)	2	0
3	Conveyor No. 1	Belt	1,134 tonne/h (1,250 tph)	1	0
4	Transfer Tower No. 1	Enclosed	N/A	1	0
5	Conveyor No. 2	Belt	1,134 tonne/h (1,250 tph)	1	0
6	As-Received Coal Sampling System	Two-stage	N/A	1	0
7	Stacker/Reclaimer	Traveling, linear	1,134 tonne/h (1,250 tph)	1	0
8	Reclaim Hopper	N/A	45 tonne (50 ton)	2	1
9	Feeder	Vibratory	191 tonne/h (210 tph)	2	1
10	Conveyor No. 3	Belt w/ tripper	372 tonne/h (410 tph)	1	0
11	Crusher Tower	N/A	N/A	1	0
12	Coal Surge Bin w/ Vent Filter	Dual outlet	191 tonne (210 ton)	2	0
13	Crusher	Impactor reduction	8 cm x 0 - 3 cm x 0 (3" x 0 - 1-1/4" x 0)	2	0
14	As-Fired Coal Sampling System	Swing hammer	N/A	1	1
15	Conveyor No. 4	Belt w/tripper	372 tonne/h (410 tph)	1	0
16	Transfer Tower No. 2	Enclosed	N/A	1	0
17	Conveyor No. 5	Belt w/ tripper	372 tonne/h (410 tph)	1	0
18	Coal Silo w/ Vent Filter and Slide Gates	Field erected	816 tonne (900 ton)	3	0
19	Limestone Truck Unloading Hopper	N/A	36 tonne (40 ton)	1	0
20	Limestone Feeder	Belt	100 tonne/h (110 tph)	1	0
21	Limestone Conveyor No. L1	Belt	100 tonne/h (110 tph)	1	0
22	Limestone Reclaim Hopper	N/A	18 tonne (20 ton)	1	0
23	Limestone Reclaim Feeder	Belt	73 tonne/h (80 tph)	1	0
24	Limestone Conveyor No. L2	Belt	73 tonne/h (80 tph)	1	0
25	Limestone Day Bin	w/ actuator	308 tonne (340 ton)	2	0

Account 2 – Coal and Sorbent Preparation and Feed

Item	Description	Type	Design Condition	Op. Qty.	Spares
1	Coal Feeder	Gravimetric	45 tonne/h (50 tph)	6	0
2	Coal Pulverizer	Ball type or equivalent	45 tonne/h (50 tph)	6	0
3	Limestone Weigh Feeder	Gravimetric	25 tonne/h (28 tph)	1	1
4	Limestone Ball Mill	Rotary	25 tonne/h (28 tph)	1	1
5	Limestone Mill Slurry Tank with Agitator	N/A	98,421 liters (26,000 gal)	1	1
6	Limestone Mill Recycle Pumps	Horizontal centrifugal	390 lpm @ 12m H2O (430 gpm @ 40 ft H2O)	1	1
7	Hydroclone Classifier	4 active cyclones in a 5 cyclone bank	100 lpm (110 gpm) per cyclone	1	1
8	Distribution Box	2-way	N/A	1	1
9	Limestone Slurry Storage Tank with Agitator	Field erected	548,889 liters (145,000 gal)	1	1
10	Limestone Slurry Feed Pumps	Horizontal centrifugal	272 lpm @ 9m H2O (300 gpm @ 30 ft H2O)	1	1

Account 3 – Feedwater and Miscellaneous Systems and Equipment

Item	Description	Type	Design Condition	Op. Qty.	Spares
1	Demineralized Water Storage Tank	Vertical, cylindrical, outdoor	1,324,904 liters (350,000 gal)	2	0
2	Condensate Pumps	Vertical canned	16,656 lpm @ 213 m H2O (4,400 gpm @ 700 ft H2O)	1	1
3	Deaerator and Storage Tank	Horizontal spray type	2,208,090 kg/h (4,868,000 lb/h), 5 min. tank	1	0
4	Boiler Feed Pump/Turbine	Barrel type, multi-stage, centrifugal	37,097 lpm @ 3,475 m H2O (9,800 gpm @ 11,400 ft H2O)	1	1
5	Startup Boiler Feed Pump, Electric Motor Driven	Barrel type, multi-stage, centrifugal	10,978 lpm @ 3,475 m H2O (2,900 gpm @ 11,400 ft H2O)	1	0
6	LP Feedwater Heater 1A/1B	Horizontal U-tube	494,416 kg/h (1,090,000 lb/h)	2	0
7	LP Feedwater Heater 2A/2B	Horizontal U-tube	494,416 kg/h (1,090,000 lb/h)	2	0
8	LP Feedwater Heater 3A/3B	Horizontal U-tube	494,416 kg/h (1,090,000 lb/h)	2	0
9	LP Feedwater Heater 4A/4B	Horizontal U-tube	494,416 kg/h (1,090,000 lb/h)	2	0
10	HP Feedwater Heater 6	Horizontal U-tube	2,208,997 kg/h (4,870,000 lb/h)	1	0
11	HP Feedwater Heater 7	Horizontal U-tube	2,208,997 kg/h (4,870,000 lb/h)	1	0
12	HP Feedwater heater 8	Horizontal U-tube	2,208,997 kg/h (4,870,000 lb/h)	1	0
13	Auxiliary Boiler	Shop fabricated, water tube	18,144 kg/h, 2.8 MPa, 343°C (40,000 lb/h, 400 psig, 650°F)	1	0
14	Fuel Oil System	No. 2 fuel oil for light off	1,135,632 liter (300,000 gal)	1	0
15	Service Air Compressors	Flooded Screw	28 m3/min @ 0.7 MPa (1,000 scfm @ 100 psig)	2	1
16	Instrument Air Dryers	Duplex, regenerative	28 m3/min (1,000 scfm)	2	1
17	Closed Cycle Cooling Heat Exchangers	Shell and tube	53 MMkJ/h (50 MMBtu/h) each	2	0
18	Closed Cycle Cooling Water Pumps	Horizontal centrifugal	20,820 lpm @ 30 m H2O (5,500 gpm @ 100 ft H2O)	2	1
19	Engine-Driven Fire Pump	Vertical turbine, diesel engine	3,785 lpm @ 88 m H2O (1,000 gpm @ 290 ft H2O)	1	1
20	Fire Service Booster Pump	Two-stage horizontal centrifugal	2,650 lpm @ 64 m H2O (700 gpm @ 210 ft H2O)	1	1

21	Raw Water Pumps	Stainless steel, single suction	21,993 lpm @ 43 m H2O (5,810 gpm @ 140 ft H2O)	2	1
22	Filtered Water Pumps	Stainless steel, single suction	1,741 lpm @ 49 m H2O (460 gpm @ 160 ft H2O)	2	1
23	Filtered Water Tank	Vertical, cylindrical	1,680,736 liter (444,000 gal)	1	0
24	Makeup Water Demineralizer	Multi-media filter, cartridge filter, RO membrane assembly, electro-deionization unit	719 lpm (190 gpm)	1	1
25	Liquid Waste Treatment System	--	10 years, 24-hour storm	1	0

Account 4 – Boiler and Accessories

Item	Description	Type	Design Condition	Op. Qty.	Spares
1	Boiler	Supercritical, drum, wall-fired, low NOx burners, overfire air	2,431,258 kg/h steam @ 24.1 MPa/593°C/593°C (5,360,000 lb/h steam @ 3,500 psig/1,100°F/1,100°F)	1	0
2	Primary Air Fan	Centrifugal	290,753 kg/h, 3,979 m3/min @ 123 cm WG (641,000 lb/h, 140,500 acfm @ 48 in. WG)	2	0
3	Forced Draft Fan	Centrifugal	945,741 kg/h, 12,949 m3/min @ 47 cm WG (2,085,000 lb/h, 457,300 acfm @19 in. WG)	2	0
4	Induced Draft Fan	Centrifugal	1,365,768 kg/h, 29,002 m3/min @ 90 cm WG (3,011,000 lb/h, 1,024,200 acfm @ 36 in. WG)	2	0
5	SCR Reactor Vessel	Space for spare layer	2,730,629 kg/h (6,020,000 lb/h)	2	0
6	SCR Catalyst	--	--	3	0
7	Dilution Air Blower	Centrifugal	161 m3/min @ 108 cm WG (5,700 acfm @ 42 in. WG)	2	1
8	Ammonia Storage	Horizontal tank	177,916 liter (47,000 gal)	5	0
9	Ammonia Feed Pump	Centrifugal	34 lpm @ 91 m H2O (9 gpm @ 300 ft H2O)	2	1

Account 5 – Flue Gas Cleanup

Item	Description	Type	Design Condition	Op. Qty.	Spares
1	Fabric Filter	Single stage, high-ratio with pulse-jet online cleaning system	1,375,294 kg/h (3,032,000 lb/h) 99.8% efficiency	2	0
2	Absorber Module	Counter-current open spray	45,789 m3/min (1,617,000 acfm)	1	0
3	Recirculation Pumps	Horizontal centrifugal	158,989 lpm @ 64 m H2O (42,000 gpm @ 210 ft H2O)	5	1
4	Bleed Pumps	Horizontal centrifugal	4,808 lpm (1,270 gpm) at 20 wt% solids	2	1
5	Oxidation Air Blowers	Centrifugal	211 m3/min @ 0.3 MPa (7,460 acfm @ 42 psia)	2	1
6	Agitators	Side entering	50 hp	5	1
7	Dewatering Cyclones	Radial assembly, 5 units each	1,211 lpm (320 gpm) per cyclone	2	0
8	Vacuum Filter Belt	Horizontal belt	38 tonne/h (42 tph) of 50 wt % slurry	2	1
9	Filtrate Water Return Pumps	Horizontal centrifugal	719 lpm @ 12 m H2O (190 gpm @ 40 ft H2O)	1	1
10	Filtrate Water Return Storage Tank	Vertical, lined	492,107 lpm (130,000 gal)	1	0
11	Process Makeup Water Pumps	Horizontal centrifugal	2,726 lpm @ 21 m H2O (720 gpm @ 70 ft H2O)	1	1

Account 5B – CO_2 Removal and Compression

Item	Description	Type	Design Condition	Op. Qty.	Spares
1	AKM24	40% AKM24 CO_2 capture technology	1,442,425 kg/h (3,180,000 lb/h) 20.6 wt% CO_2 concentration	2	0
2	CO_2 Compressor	Multi-stage integrally-geared centrifugal	266,677 kg/h @ 15.3 MPa (587,923 lb/h @ 2,215 psia)	2	0

Account 6 – Combustion Turbine and Accessories

N/A

Account 7 – HRSG, Ducting & Stack

Item	Description	Type	Design Condition	Op. Qty.	Spares
1	Stack	Reinforced concrete with FRP liner	152 m (500 ft) high x 5.5 m (18 ft) diameter	1	0

Account 8 – Steam Turbine Generator and Auxiliaries

Item	Description	Type	Design Condition	Op. Qty.	Spares
1	Steam Turbine	Commercially available advanced steam turbine	710 MW, 24.1 MPa/593°C/593°C (3500 psig/ 1100°F/1100°F)	1	0
2	Steam Turbine Generator	Hydrogen cooled, static excitation	790 MVA @ 0.9 p.f., 24 kV, 60 Hz	1	0
3	Surface Condenser	Single pass, divided waterbox including vacuum pumps	1,813 MMkJ/h (1,720 MMBtu/h), Inlet water temperature 16ºC (60ºF), Water temperature rise 11ºC (20ºF)	1	0

Account 9 – Cooling Water System

Item	Description	Type	Design Condition	Op. Qty.	Spares
1	Circulating Water Pumps	Vertical, wet pit	529,962 lpm @ 30.5 m (140,000 gpm @ 100 ft)	4	2
2	Cooling Tower	Evaporative, mechanical draft, multi-cell	11°C (51.5°F) wet bulb / 16°C (60°F) CWT / 27°C (80°F) HWT 5,113 MMkJ/h (4,850 MMBtu/h) heat load	1	0

Account 10 – Ash/Spent Sorbent Recovery and Handling

Item	Description	Type	Design Condition	Op. Qty.	Spares
1	Economizer Hopper (part of boiler scope of supply)	--	--	4	0
2	Bottom Ash Hopper (part of boiler scope of supply)	--	--	2	0
3	Clinker Grinder	--	4.5 tonne/h (5 tph)	1	1
4	Pyrites Hopper (part of pulverizer scope of supply included with boiler)	--	--	6	0
5	Hydroejectors	--	--	12	
6	Economizer /Pyrites Transfer Tank	--	--	1	0
7	Ash Sluice Pumps	Vertical, wet pit	189 lpm @ 17 m H2O (50 gpm @ 56 ft H2O)	1	1
8	Ash Seal Water Pumps	Vertical, wet pit	7,571 lpm @ 9 m H2O (2000 gpm @ 28 ft H2O)	1	1
9	Hydrobins	--	189 lpm (50 gpm)	1	1
10	Baghouse Hopper (part of baghouse scope of supply)	--	--	24	0
11	Air Heater Hopper (part of boiler scope of supply)	--	--	10	0
12	Air Blower	--	18 m3/min @ 0.2 MPa (630 scfm @ 24 psi)	1	1
13	Fly Ash Silo	Reinforced concrete	590 tonne (1,300 ton)	2	0
14	Slide Gate Valves	--	--	2	0
15	Unloader	--	--	1	0
16	Telescoping Unloading Chute	--	109 tonne/h (120 tph)	1	0

Account 11 – Accessory Electric Plant

Item	Description	Type	Design Condition	Op. Qty.	Spares
1	STG Transformer	Oil-filled	24 kV/345 kV, 790 MVA, 3-ph, 60 Hz	1	0
2	Auxiliary Transformer	Oil-filled	24 kV/4.16 kV, 141 MVA, 3-ph, 60 Hz	1	1
3	Low Voltage Transformer	Dry ventilated	4.16 kV/480 V, 21 MVA, 3-ph, 60 Hz	1	1
4	STG Isolated Phase Bus Duct and Tap Bus	Aluminum, self-cooled	24 kV, 3-ph, 60 Hz	1	0
5	Medium Voltage Switchgear	Metal clad	4.16 kV, 3-ph, 60 Hz	1	1
6	Low Voltage Switchgear	Metal enclosed	480 V, 3-ph, 60 Hz	1	1
7	Emergency Diesel Generator	Sized for emergency shutdown	750 kW, 480 V, 3-ph, 60 Hz	1	0

Account 12 – Instrumentation and Control

Item	Description	Type	Design Condition	Op. Qty.	Spares
1	DCS - Main Control	Monitor/keyboard; Operator printer (laser color); Engineering printer (laser B&W)	Operator stations/printers and engineering stations/printers	1	0
2	DCS - Processor	Microprocessor with redundant input/output	N/A	1	0
3	DCS - Data Highway	Fiber optic	Fully redundant, 25% spare	1	0

A2.2 Case-2A Major Equipment List

Account 1 - Fuel and Sorbent Handling

Item	Description	Type	Design Condition	Op. Qty.	Spares
1	Bottom Trestle Dumper and Receiving Hoppers	N/A	181 tonne (200 ton)	2	0
2	Feeder	Belt	572 tonne/h (630 tph)	2	0
3	Conveyor No. 1	Belt	1,134 tonne/h (1,250 tph)	1	0
4	Transfer Tower No. 1	Enclosed	N/A	1	0
5	Conveyor No. 2	Belt	1,134 tonne/h (1,250 tph)	1	0
6	As-Received Coal Sampling System	Two-stage	N/A	1	0
7	Stacker/Reclaimer	Traveling, linear	1,134 tonne/h (1,250 tph)	1	0
8	Reclaim Hopper	N/A	45 tonne (50 ton)	2	1
9	Feeder	Vibratory	181 tonne/h (200 tph)	2	1
10	Conveyor No. 3	Belt w/ tripper	372 tonne/h (410 tph)	1	0
11	Crusher Tower	N/A	N/A	1	0
12	Coal Surge Bin w/ Vent Filter	Dual outlet	181 tonne (200 ton)	2	0
13	Crusher	Impactor reduction	8 cm x 0 - 3 cm x 0 (3" x 0 - 1-1/4" x 0)	2	0
14	As-Fired Coal Sampling System	Swing hammer	N/A	1	1
15	Conveyor No. 4	Belt w/tripper	372 tonne/h (410 tph)	1	0
16	Transfer Tower No. 2	Enclosed	N/A	1	0
17	Conveyor No. 5	Belt w/ tripper	372 tonne/h (410 tph)	1	0
18	Coal Silo w/ Vent Filter and Slide Gates	Field erected	816 tonne (900 ton)	3	0
19	Limestone Truck Unloading Hopper	N/A	36 tonne (40 ton)	1	0
20	Limestone Feeder	Belt	91 tonne/h (100 tph)	1	0
21	Limestone Conveyor No. L1	Belt	91 tonne/h (100 tph)	1	0
22	Limestone Reclaim Hopper	N/A	18 tonne (20 ton)	1	0
23	Limestone Reclaim Feeder	Belt	73 tonne/h (80 tph)	1	0
24	Limestone Conveyor No. L2	Belt	73 tonne/h (80 tph)	1	0
25	Limestone Day Bin	w/ actuator	299 tonne (330 ton)	2	0

Account 2 – Coal and Sorbent Preparation and Feed

Item	Description	Type	Design Condition	Op. Qty.	Spares
1	Coal Feeder	Gravimetric	45 tonne/h (50 tph)	6	0
2	Coal Pulverizer	Ball type or equivalent	45 tonne/h (50 tph)	6	0
3	Limestone Weigh Feeder	Gravimetric	24 tonne/h (27 tph)	1	1
4	Limestone Ball Mill	Rotary	24 tonne/h (27 tph)	1	1
5	Limestone Mill Slurry Tank with Agitator	N/A	98,421 liters (26,000 gal)	1	1
6	Limestone Mill Recycle Pumps	Horizontal centrifugal	390 lpm @ 12m H2O (430 gpm @ 40 ft H2O)	1	1
7	Hydroclone Classifier	4 active cyclones in a 5 cyclone bank	100 lpm (110 gpm) per cyclone	1	1
8	Distribution Box	2-way	N/A	1	1
9	Limestone Slurry Storage Tank with Agitator	Field erected	537,533 liters (142,000 gal)	1	1
10	Limestone Slurry Feed Pumps	Horizontal centrifugal	272 lpm @ 9m H2O (300 gpm @ 30 ft H2O)	1	1

Account 3 – Feedwater and Miscellaneous Systems and Equipment

Item	Description	Type	Design Condition	Op. Qty.	Spares
1	Demineralized Water Storage Tank	Vertical, cylindrical, outdoor	1,302,192 liters (344,000 gal)	2	0
2	Condensate Pumps	Vertical canned	18,170 lpm @ 213 m H2O (4,800 gpm @ 700 ft H2O)	1	1
3	Deaerator and Storage Tank	Horizontal spray type	2,168,174 kg/h (4,780,000 lb/h), 5 min. tank	1	0
4	Boiler Feed Pump/Turbine	Barrel type, multi-stage, centrifugal	36,340 lpm @ 3,475 m H2O (9,600 gpm @ 11,400 ft H2O)	1	1
5	Startup Boiler Feed Pump, Electric Motor Driven	Barrel type, multi-stage, centrifugal	10,978 lpm @ 3,475 m H2O (2,900 gpm @ 11,400 ft H2O)	1	0
6	LP Feedwater Heater 1A/1B	Horizontal U-tube	539,776 kg/h (1,190,000 lb/h)	2	0
7	LP Feedwater Heater 2A/2B	Horizontal U-tube	539,776 kg/h (1,190,000 lb/h)	2	0
8	LP Feedwater Heater 3A/3B	Horizontal U-tube	539,776 kg/h (1,190,000 lb/h)	2	0
9	LP Feedwater Heater 4A/4B	Horizontal U-tube	539,776 kg/h (1,190,000 lb/h)	2	0
10	HP Feedwater Heater 6	Horizontal U-tube	2,168,174 kg/h (4,780,000 lb/h)	1	0
11	HP Feedwater Heater 7	Horizontal U-tube	2,168,174 kg/h (4,780,000 lb/h)	1	0
12	HP Feedwater heater 8	Horizontal U-tube	2,168,174 kg/h (4,780,000 lb/h)	1	0
13	Auxiliary Boiler	Shop fabricated, water tube	18,144 kg/h, 2.8 MPa, 343°C (40,000 lb/h, 400 psig, 650°F)	1	0
14	Fuel Oil System	No. 2 fuel oil for light off	1,135,632 liter (300,000 gal)	1	0
15	Service Air Compressors	Flooded Screw	28 m3/min @ 0.7 MPa (1,000 scfm @ 100 psig)	2	1
16	Instrument Air Dryers	Duplex, regenerative	28 m3/min (1,000 scfm)	2	1
17	Closed Cycle Cooling Heat Exchangers	Shell and tube	53 MMkJ/h (50 MMBtu/h) each	2	0
18	Closed Cycle Cooling Water Pumps	Horizontal centrifugal	20,820 lpm @ 30 m H2O (5,500 gpm @ 100 ft H2O)	2	1
19	Engine-Driven Fire Pump	Vertical turbine, diesel engine	3,785 lpm @ 88 m H2O (1,000 gpm @ 290 ft H2O)	1	1
20	Fire Service Booster Pump	Two-stage horizontal centrifugal	2,650 lpm @ 64 m H2O (700 gpm @ 210 ft H2O)	1	1
21	Raw Water Pumps	Stainless steel, single suction	22,372 lpm @ 43 m H2O (5,910 gpm @ 140 ft H2O)	2	1
22	Filtered Water Pumps	Stainless steel, single suction	1,703 lpm @ 49 m H2O (450 gpm @ 160 ft H2O)	2	1

23	Filtered Water Tank	Vertical, cylindrical	1,639,096 liter (433,000 gal)	1	0
24	Makeup Water Demineralizer	Multi-media filter, cartridge filter, RO membrane assembly, electro-deionization unit	719 lpm (190 gpm)	1	1
25	Liquid Waste Treatment System	--	10 years, 24-hour storm	1	0

Account 4 – Boiler and Accessories

Item	Description	Type	Design Condition	Op. Qty.	Spare s
1	Boiler	Supercritical, drum, wall-fired, low NOx burners, overfire air	2,385,899 kg/h steam @ 24.1 MPa/593°C/593°C (5,260,000 lb/h steam @ 3,500 psig/1,100°F/1,100°F)	1	0
2	Primary Air Fan	Centrifugal	285,310 kg/h, 3,905 m3/min @ 123 cm WG (629,000 lb/h, 137,900 acfm @ 48 in. WG)	2	0
3	Forced Draft Fan	Centrifugal	928,505 kg/h, 12,714 m3/min @ 47 cm WG (2,047,000 lb/h, 449,000 acfm @ 19 in. WG)	2	0
4	Induced Draft Fan	Centrifugal	1,340,821 kg/h, 28,473 m3/min @ 90 cm WG (2,956,000 lb/h, 1,005,500 acfm @ 36 in. WG)	2	0
5	SCR Reactor Vessel	Space for spare layer	2,680,734 kg/h (5,910,000 lb/h)	2	0
6	SCR Catalyst	--	--	3	0
7	Dilution Air Blower	Centrifugal	159 m3/min @ 108 cm WG (5,600 acfm @ 42 in. WG)	2	1
8	Ammonia Storage	Horizontal tank	174,130 liter (46,000 gal)	5	0
9	Ammonia Feed Pump	Centrifugal	34 lpm @ 91 m H2O (9 gpm @ 300 ft H2O)	2	1

Account 5 – Flue Gas Cleanup

Item	Description	Type	Design Condition	Op. Qty.	Spares
1	Fabric Filter	Single stage, high-ratio with pulse-jet online cleaning system	1,350,346 kg/h (2,977,000 lb/h) 99.8% efficiency	2	0
2	Absorber Module	Counter-current open spray	44,939 m3/min (1,587,000 acfm)	1	0
3	Recirculation Pumps	Horizontal centrifugal	155,203 lpm @ 64 m H2O (41,000 gpm @ 210 ft H2O)	5	1
4	Bleed Pumps	Horizontal centrifugal	4,732 lpm (1,250 gpm) at 20 wt% solids	2	1
5	Oxidation Air Blowers	Centrifugal	208 m3/min @ 0.3 MPa (7,330 acfm @ 42 psia)	2	1
6	Agitators	Side entering	50 hp	5	1
7	Dewatering Cyclones	Radial assembly, 5 units each	1,173 lpm (310 gpm) per cyclone	2	0
8	Vacuum Filter Belt	Horizontal belt	37 tonne/h (41 tph) of 50 wt % slurry	2	1
9	Filtrate Water Return Pumps	Horizontal centrifugal	719 lpm @ 12 m H2O (190 gpm @ 40 ft H2O)	1	1
10	Filtrate Water Return Storage Tank	Vertical, lined	454,253 lpm (120,000 gal)	1	0
11	Process Makeup Water Pumps	Horizontal centrifugal	2,688 lpm @ 21 m H2O (710 gpm @ 70 ft H2O)	1	1

Account 5B – CO_2 Removal and Compression

Item	Description	Type	Design Condition	Op. Qty.	Spares
1	AKM24	35% AKM24 CO_2 capture technology	1,416,117 kg/h (3,122,000 lb/h) 20.6 wt% CO_2 concentration	2	0
2	CO_2 Compressor	Multi-stage integrally-geared centrifugal	262,288 kg/h @ 15.3 MPa (578,246 lb/h @ 2,215 psia)	2	0

Account 6 – Combustion Turbine and Accessories

N/A

Account 7 – HRSG, Ducting & Stack

Item	Description	Type	Design Condition	Op. Qty.	Spares
1	Stack	Reinforced concrete with FRP liner	152 m (500 ft) high x 5.2 m (17 ft) diameter	1	0

Account 8 – Steam Turbine Generator and Auxiliaries

Item	Description	Type	Design Condition	Op. Qty.	Spares
1	Steam Turbine	Commercially available advanced steam turbine	690 MW 24.1 MPa/593°C/593°C (3500 psig/ 1100°F/1100°F)	1	0
2	Steam Turbine Generator	Hydrogen cooled, static excitation	770 MVA @ 0.9 p.f., 24 kV, 60 Hz	1	0
3	Surface Condenser	Single pass, divided waterbox including vacuum pumps	1,971 MMkJ/h (1,870 MMBtu/h), Inlet water temperature 16ºC (60ºF), Water temperature rise 11ºC (20ºF)	1	0

Account 9 – Cooling Water System

Item	Description	Type	Design Condition	Op. Qty.	Spares
1	Circulating Water Pumps	Vertical, wet pit	537,533 lpm @ 30.5 m (142,000 gpm @ 100 ft)	4	2
2	Cooling Tower	Evaporative, mechanical draft, multi-cell	11°C (51.5°F) wet bulb / 16°C (60°F) CWT / 27°C (80°F) HWT 5,218 MMkJ/h (4,950 MMBtu/h) heat load	1	0

Account 10 – Ash/Spent Sorbent Recovery and Handling

Item	Description	Type	Design Condition	Op. Qty.	Spares
1	Economizer Hopper (part of boiler scope of supply)	--	--	4	0
2	Bottom Ash Hopper (part of boiler scope of supply)	--	--	2	0
3	Clinker Grinder	--	4.5 tonne/h (5 tph)	1	1
4	Pyrites Hopper (part of pulverizer scope of supply included with boiler)	--	--	6	0
5	Hydroejectors	--	--	12	
6	Economizer /Pyrites Transfer Tank	--	--	1	0
7	Ash Sluice Pumps	Vertical, wet pit	189 lpm @ 17 m H2O (50 gpm @ 56 ft H2O)	1	1
8	Ash Seal Water Pumps	Vertical, wet pit	7,571 lpm @ 9 m H2O (2000 gpm @ 28 ft H2O)	1	1
9	Hydrobins	--	189 lpm (50 gpm)	1	1
10	Baghouse Hopper (part of baghouse scope of supply)	--	--	24	0
11	Air Heater Hopper (part of boiler scope of supply)	--	--	10	0
12	Air Blower	--	18 m3/min @ 0.2 MPa (620 scfm @ 24 psi)	1	1
13	Fly Ash Silo	Reinforced concrete	590 tonne (1,300 ton)	2	0
14	Slide Gate Valves	--	--	2	0
15	Unloader	--	--	1	0
16	Telescoping Unloading Chute	--	109 tonne/h (120 tph)	1	0

Account 11 – Accessory Electric Plant

Item	Description	Type	Design Condition	Op. Qty.	Spares
1	STG Transformer	Oil-filled	24 kV/345 kV, 770 MVA,3-ph, 60 Hz	1	0
2	Auxiliary Transformer	Oil-filled	24 kV/4.16 kV, 118 MVA, 3-ph, 60 Hz	1	1
3	Low Voltage Transformer	Dry ventilated	4.16 kV/480 V, 18 MVA, 3-ph, 60 Hz	1	1
4	STG Isolated Phase Bus Duct and Tap Bus	Aluminum, self-cooled	24 kV, 3-ph, 60 Hz	1	0
5	Medium Voltage Switchgear	Metal clad	4.16 kV, 3-ph, 60 Hz	1	1
6	Low Voltage Switchgear	Metal enclosed	480 V, 3-ph, 60 Hz	1	1
7	Emergency Diesel Generator	Sized for emergency shutdown	750 kW, 480 V, 3-ph, 60 Hz	1	0

Account 12 – Instrumentation and Control

Item	Description	Type	Design Condition	Op. Qty.	Spares
1	DCS - Main Control	Monitor/keyboard; Operator printer (laser color); Engineering printer (laser B&W)	Operator stations/printers and engineering stations/printers	1	0
2	DCS - Processor	Microprocessor with redundant input/output	N/A	1	0
3	DCS - Data Highway	Fiber optic	Fully redundant, 25% spare	1	0

A2.3 Case-2B Major Equipment List

Account 1 - Fuel and Sorbent Handling

Item	Description	Type	Design Condition	Op. Qty.	Spares
1	Bottom Trestle Dumper and Receiving Hoppers	N/A	181 tonne (200 ton)	2	0
2	Feeder	Belt	572 tonne/h (630 tph)	2	0
3	Conveyor No. 1	Belt	1,134 tonne/h (1,250 tph)	1	0
4	Transfer Tower No. 1	Enclosed	N/A	1	0
5	Conveyor No. 2	Belt	1,134 tonne/h (1,250 tph)	1	0
6	As-Received Coal Sampling System	Two-stage	N/A	1	0
7	Stacker/Reclaimer	Traveling, linear	1,134 tonne/h (1,250 tph)	1	0
8	Reclaim Hopper	N/A	45 tonne (50 ton)	2	1
9	Feeder	Vibratory	181 tonne/h (200 tph)	2	1
10	Conveyor No. 3	Belt w/ tripper	363 tonne/h (400 tph)	1	0
11	Crusher Tower	N/A	N/A	1	0
12	Coal Surge Bin w/ Vent Filter	Dual outlet	181 tonne (200 ton)	2	0
13	Crusher	Impactor reduction	8 cm x 0 - 3 cm x 0 (3" x 0 - 1-1/4" x 0)	2	0
14	As-Fired Coal Sampling System	Swing hammer	N/A	1	1
15	Conveyor No. 4	Belt w/tripper	363 tonne/h (400 tph)	1	0
16	Transfer Tower No. 2	Enclosed	N/A	1	0
17	Conveyor No. 5	Belt w/ tripper	363 tonne/h (400 tph)	1	0
18	Coal Silo w/ Vent Filter and Slide Gates	Field erected	816 tonne (900 ton)	3	0
19	Limestone Truck Unloading Hopper	N/A	36 tonne (40 ton)	1	0
20	Limestone Feeder	Belt	91 tonne/h (100 tph)	1	0
21	Limestone Conveyor No. L1	Belt	91 tonne/h (100 tph)	1	0
22	Limestone Reclaim Hopper	N/A	18 tonne (20 ton)	1	0
23	Limestone Reclaim Feeder	Belt	73 tonne/h (80 tph)	1	0
24	Limestone Conveyor No. L2	Belt	73 tonne/h (80 tph)	1	0
25	Limestone Day Bin	w/ actuator	299 tonne (330 ton)	2	0

Account 2 – Coal and Sorbent Preparation and Feed

Item	Description	Type	Design Condition	Op. Qty.	Spares
1	Coal Feeder	Gravimetric	36 tonne/h (40 tph)	6	0
2	Coal Pulverizer	Ball type or equivalent	36 tonne/h (40 tph)	6	0
3	Limestone Weigh Feeder	Gravimetric	24 tonne/h (27 tph)	1	1
4	Limestone Ball Mill	Rotary	24 tonne/h (27 tph)	1	1
5	Limestone Mill Slurry Tank with Agitator	N/A	94,636 liters (25,000 gal)	1	1
6	Limestone Mill Recycle Pumps	Horizontal centrifugal	372 lpm @ 12m H_2O (410 gpm @ 40 ft H_2O)	1	1
7	Hydroclone Classifier	4 active cyclones in a 5 cyclone bank	91 lpm (100 gpm) per cyclone	1	1
8	Distribution Box	2-way	N/A	1	1
9	Limestone Slurry Storage Tank with Agitator	Field erected	533,747 liters (141,000 gal)	1	1
10	Limestone Slurry Feed Pumps	Horizontal centrifugal	263 lpm @ 9m H_2O (290 gpm @ 30 ft H_2O)	1	1

Account 3 – Feedwater and Miscellaneous Systems and Equipment

Item	Description	Type	Design Condition	Op. Qty.	Spares
1	Demineralized Water Storage Tank	Vertical, cylindrical, outdoor	1,294,621 liters (342,000 gal)	2	0
2	Condensate Pumps	Vertical canned	19,306 lpm @ 213 m H2O (5,100 gpm @ 700 ft H2O)	1	1
3	Deaerator and Storage Tank	Horizontal spray type	2,156,834 kg/h (4,755,000 lb/h), 5 min. tank	1	0
4	Boiler Feed Pump/Turbine	Barrel type, multi-stage, centrifugal	36,340 lpm @ 3,475 m H2O (9,600 gpm @ 11,400 ft H2O)	1	1
5	Startup Boiler Feed Pump, Electric Motor Driven	Barrel type, multi-stage, centrifugal	10,978 lpm @ 3,475 m H2O (2,900 gpm @ 11,400 ft H2O)	1	0
6	LP Feedwater Heater 1A/1B	Horizontal U-tube	576,063 kg/h (1,270,000 lb/h)	2	0
7	LP Feedwater Heater 2A/2B	Horizontal U-tube	576,063 kg/h (1,270,000 lb/h)	2	0
8	LP Feedwater Heater 3A/3B	Horizontal U-tube	576,063 kg/h (1,270,000 lb/h)	2	0
9	LP Feedwater Heater 4A/4B	Horizontal U-tube	576,063 kg/h (1,270,000 lb/h)	2	0
10	HP Feedwater Heater 6	Horizontal U-tube	2,159,102 kg/h (4,760,000 lb/h)	1	0
11	HP Feedwater Heater 7	Horizontal U-tube	2,159,102 kg/h (4,760,000 lb/h)	1	0
12	HP Feedwater heater 8	Horizontal U-tube	2,159,102 kg/h (4,760,000 lb/h)	1	0
13	Auxiliary Boiler	Shop fabricated, water tube	18,144 kg/h, 2.8 MPa, 343°C (40,000 lb/h, 400 psig, 650°F)	1	0
14	Fuel Oil System	No. 2 fuel oil for light off	1,135,632 liter (300,000 gal)	1	0
15	Service Air Compressors	Flooded Screw	28 m3/min @ 0.7 MPa (1,000 scfm @ 100 psig)	2	1
16	Instrument Air Dryers	Duplex, regenerative	28 m3/min (1,000 scfm)	2	1
17	Closed Cycle Cooling Heat Exchangers	Shell and tube	53 MMkJ/h (50 MMBtu/h) each	2	0
18	Closed Cycle Cooling Water Pumps	Horizontal centrifugal	20,820 lpm @ 30 m H2O (5,500 gpm @ 100 ft H2O)	2	1
19	Engine-Driven Fire Pump	Vertical turbine, diesel engine	3,785 lpm @ 88 m H2O (1,000 gpm @ 290 ft H2O)	1	1
20	Fire Service Booster Pump	Two-stage horizontal centrifugal	2,650 lpm @ 64 m H2O (700 gpm @ 210 ft H2O)	1	1
21	Raw Water Pumps	Stainless steel, single suction	22,902 lpm @ 43 m H2O (6,050 gpm @ 140 ft H2O)	2	1
22	Filtered Water Pumps	Stainless steel, single suction	1,703 lpm @ 49 m H2O (450 gpm @ 160 ft H2O)	2	1
23	Filtered Water Tank	Vertical, cylindrical	1,639,096 liter (433,000 gal)	1	0

24	Makeup Water Demineralizer	Multi-media filter, cartridge filter, RO membrane assembly, electro-deionization unit	719 lpm (190 gpm)	1	1
25	Liquid Waste Treatment System	--	10 years, 24-hour storm	1	0

Account 4 – Boiler and Accessories

Item	Description	Type	Design Condition	Op. Qty.	Spares
1	Boiler	Supercritical, drum, wall-fired, low NOx burners, overfire air	2,372,291 kg/h steam @ 24.1 MPa/593°C/593°C (5,230,000 lb/h steam @ 3,500 psig/1,100°F/1,100°F)	1	0
2	Primary Air Fan	Centrifugal	283,949 kg/h, 3,885 m3/min @ 123 cm WG (626,000 lb/h, 137,200 acfm @ 48 in. WG)	2	0
3	Forced Draft Fan	Centrifugal	923,969 kg/h, 12,649 m3/min @ 47 cm WG (2,037,000 lb/h, 446,700 acfm @ 19 in. WG)	2	0
4	Induced Draft Fan	Centrifugal	1,334,017 kg/h, 28,325 m3/min @ 90 cm WG (2,941,000 lb/h, 1,000,300 acfm @ 36 in. WG)	2	0
5	SCR Reactor Vessel	Space for spare layer	2,667,126 kg/h (5,880,000 lb/h)	2	0
6	SCR Catalyst	--	--	3	0
7	Dilution Air Blower	Centrifugal	159 m3/min @ 108 cm WG (5,600 acfm @ 42 in. WG)	2	1
8	Ammonia Storage	Horizontal tank	174,130 liter (46,000 gal)	5	0
9	Ammonia Feed Pump	Centrifugal	33 lpm @ 91 m H2O (9 gpm @ 300 ft H2O)	2	1

Account 5 – Flue Gas Cleanup

Item	Description	Type	Design Condition	Op. Qty.	Spares
1	Fabric Filter	Single stage, high-ratio with pulse-jet online cleaning system	1,343,089 kg/h (2,961,000 lb/h) 99.8% efficiency	2	0
2	Absorber Module	Counter-current open spray	44,713 m3/min (1,579,000 acfm)	1	0
3	Recirculation Pumps	Horizontal centrifugal	155,203 lpm @ 64 m H2O (41,000 gpm @ 210 ft H2O)	5	1
4	Bleed Pumps	Horizontal centrifugal	4,694 lpm (1,240 gpm) at 20 wt% solids	2	1
5	Oxidation Air Blowers	Centrifugal	206 m3/min @ 0.3 MPa (7,290 acfm @ 42 psia)	2	1
6	Agitators	Side entering	50 hp	5	1
7	Dewatering Cyclones	Radial assembly, 5 units each	1,173 lpm (310 gpm) per cyclone	2	0
8	Vacuum Filter Belt	Horizontal belt	37 tonne/h (41 tph) of 50 wt % slurry	2	1
9	Filtrate Water Return Pumps	Horizontal centrifugal	719 lpm @ 12 m H2O (190 gpm @ 40 ft H2O)	1	1
10	Filtrate Water Return Storage Tank	Vertical, lined	454,253 lpm (120,000 gal)	1	0
11	Process Makeup Water Pumps	Horizontal centrifugal	2,688 lpm @ 21 m H2O (710 gpm @ 70 ft H2O)	1	1

Account 5B – CO_2 Removal and Compression

Item	Description	Type	Design Condition	Op. Qty.	Spares
1	AKM24	35% AKM24 CO_2 capture technology	1,408,860 kg/h (3,106,000 lb/h) 20.6 wt% CO_2 concentration	2	0
2	CO_2 Compressor	Multi-stage integrally-geared centrifugal	262,039 kg/h @ 15.3 MPa (577,696 lb/h @ 2,215 psia)	2	0

Account 6 – Combustion Turbine and Accessories

N/A

Account 7 – HRSG, Ducting & Stack

Item	Description	Type	Design Condition	Op. Qty.	Spares
1	Stack	Reinforced concrete with FRP liner	152 m (500 ft) high x 5.2 m (17 ft) diameter	1	0

Account 8 – Steam Turbine Generator and Auxiliaries

Item	Description	Type	Design Condition	Op. Qty.	Spares
1	Steam Turbine	Commercially available advanced steam turbine	680 MW 24.1 MPa/593°C/593°C (3500 psig/ 1100°F/1100°F)	1	0
2	Steam Turbine Generator	Hydrogen cooled, static excitation	760 MVA @ 0.9 p.f., 24 kV, 60 Hz	1	0
3	Surface Condenser	Single pass, divided waterbox including vacuum pumps	2,119 MMkJ/h (2,010 MMBtu/h), Inlet water temperature 16ºC (60ºF), Water temperature rise 11ºC (20ºF)	1	0

Account 9 – Cooling Water System

Item	Description	Type	Design Condition	Op. Qty.	Spares
1	Circulating Water Pumps	Vertical, wet pit	552,674 lpm @ 30.5 m (146,000 gpm @ 100 ft)	4	2
2	Cooling Tower	Evaporative, mechanical draft, multi-cell	11°C (51.5°F) wet bulb / 16°C (60°F) CWT / 27°C (80°F) HWT 5,366 MMkJ/h (5,090 MMBtu/h) heat load	1	0

Account 10 – Ash/Spent Sorbent Recovery and Handling

Item	Description	Type	Design Condition	Op. Qty..	Spares
1	Economizer Hopper (part of boiler scope of supply)	--	--	4	0
2	Bottom Ash Hopper (part of boiler scope of supply)	--	--	2	0
3	Clinker Grinder	--	4.5 tonne/h (5 tph)	1	1
4	Pyrites Hopper (part of pulverizer scope of supply included with boiler)	--	--	6	0
5	Hydroejectors	--	--	12	
6	Economizer /Pyrites Transfer Tank	--	--	1	0
7	Ash Sluice Pumps	Vertical, wet pit	189 lpm @ 17 m H2O (50 gpm @ 56 ft H2O)	1	1
8	Ash Seal Water Pumps	Vertical, wet pit	7,571 lpm @ 9 m H2O (2000 gpm @ 28 ft H2O)	1	1
9	Hydrobins	--	189 lpm (50 gpm)	1	1
10	Baghouse Hopper (part of baghouse scope of supply)	--	--	24	0
11	Air Heater Hopper (part of boiler scope of supply)	--	--	10	0
12	Air Blower	--	17 m3/min @ 0.2 MPa (610 scfm @ 24 psi)	1	1
13	Fly Ash Silo	Reinforced concrete	590 tonne (1,300 ton)	2	0
14	Slide Gate Valves	--	--	2	0
15	Unloader	--	--	1	0
16	Telescoping Unloading Chute	--	109 tonne/h (120 tph)	1	0

Account 11 – Accessory Electric Plant

Item	Description	Type	Design Condition	Op. Qty.	Spares
1	STG Transformer	Oil-filled	24 kV/345 kV, 750 MVA, 3-ph, 60 Hz	1	0
2	Auxiliary Transformer	Oil-filled	24 kV/4.16 kV, 103 MVA, 3-ph, 60 Hz	1	1
3	Low Voltage Transformer	Dry ventilated	4.16 kV/480 V, 15 MVA, 3-ph, 60 Hz	1	1
4	STG Isolated Phase Bus Duct & Tap Bus	Aluminum, self-cooled	24 kV, 3-ph, 60 Hz	1	0
5	Medium Voltage Switchgear	Metal clad	4.16 kV, 3-ph, 60 Hz	1	1
6	Low Voltage Switchgear	Metal enclosed	480 V, 3-ph, 60 Hz	1	1
7	Emergency Diesel Generator	Sized for emergency shutdown	750 kW, 480 V, 3-ph, 60 Hz	1	0

Account 12 – Instrumentation and Control

Item	Description	Type	Design Condition	Op. Qty.	Spares
1	DCS - Main Control	Monitor/keyboard; Operator printer (laser color); Engineering printer (laser B&W)	Operator stations/printers and engineering stations/printers	1	0
2	DCS - Processor	Microprocessor with redundant input/output	N/A	1	0
3	DCS - Data Highway	Fiber optic	Fully redundant, 25% spare	1	0

Appendix 3: Key Preliminary TEA Results, Rev. Nov. 2014

Exhibit A3-1: Comparative Plant Performance Summary (Rev. Nov 2014)

	BBS Case 11	BBS Case 12	AKM-24 Case-1A	AKM-24 Case-2A	AKM-24 Case-2B
Steam Turbine Gross Power, kWe	**580,400**	**662,800**	**676,784**	**656,349**	**643,040**
AUXILIARY LOAD SUMMARY, kWe					
Coal Handling and Conveying	440	510	452	444	442
Pulverizers	2,780	3,850	3,415	3,353	3,335
Sorbent Handling & Reagent Preparation	890	1,250	1,109	1,089	1,083
Ash Handling	530	740	656	644	641
Primary Air Fans	1,300	1,800	1,596	1,567	1,559
Forced Draft Fans	1,660	2,300	2,040	2,003	1,993
Induced Draft Fans	7,050	11,120	9,863	9,683	9,633
SCR	50	70	62	61	61
Baghouse	70	100	89	87	87
Wet FGD	2,970	4,110	3,645	3,579	3,561
CO_2 Capture System Auxiliaries	0	20,600	9,467	9,121	8,957
CO_2 System Vacuum Blower	0	0	36,385	17,757	4,885
CO_2 Compression	0	44,890	39,685	39,032	38,994
Miscellaneous Balance of Plant	2,000	2,000	1,770	1,740	1,730
Steam Turbine Auxiliaries	400	400	408	396	388
Condensate Pumps	800	560	566	619	661
Circulating Water Pumps	4,730	10,100	8,195	7,990	7,889
Ground Water Pumps	480	910	802	787	783
Cooling Tower Fans	2,440	5,230	4,243	4,137	4,085
Transformer Loss	1,820	2,290	2,338	2,268	2,222
TOTAL AUXILIARIES, kWe	**30,410**	**112,830**	**126,786**	**106,356**	**92,989**
NET PLANT POWER	549,990	549,970	549,998	549,993	550,051
Net Plant Efficiency (HHV)	39.3%	28.4%	32.1%	32.6%	32.8%
Net Plant Heat Rate, Btu/kWh (HHV)	8,687	12,002	10,645	10,451	10,396
Net Plant Heat Rate, kJ/kWh (HHV)	9,164	12,662	11,230	11,026	10,968
CONDENSER COOLING DUTY, MMBTU/hr	2,178	1,646	1,563	1,704	1,826
CONDENSER COOLING DUTY, kWth	638,309	482,395	458,070	499,393	535,148
CO_2 Capture					
Flue Gas into Capture System, lb/hr	4,713,221	6,518,035	5,781,125	5,675,950	5,646,691
Flue Gas into Capture System, kg/hr	2,137,917	2,956,581	2,622,318	2,574,611	2,561,339
CO_2 Captured, lb/hr	N/A	1,209,158	1,068,950	1,051,356	1,050,356
CO_2 Captured, kg/hr	N/A	548,474	484,876	476,895	476,441
Steam Extracted for CO_2 Capture System					
Flow, lb/hr	N/A	1,784,175	1,259,886	1,074,689	1,002,089
Flow, kg/hr	N/A	809,302	571,485	487,479	454,547
Temperature, °F	N/A	556	158	194	242
Temperature, °C	N/A	291	70	90	116
Pressure, psia	N/A	73.5	4.6	10.1	25.5
Pressure, MPa	N/A	0.51	0.03	0.07	0.18

	BBS Case 11	BBS Case 12	AKM-24 Case-1A	AKM-24 Case-2A	AKM-24 Case-2B
CONSUMABLES					
As-Received Coal Feed, lb/hr	409,528	565,820	501,850	492,720	490,180
As-Received Coal Feed, kg/hr	185,762	256,656	227,639	223,498	222,346
Thermal Input, kWt	1,400,162	1,934,519	1,715,808	1,684,593	1,675,908
Limestone Sorbent Feed, lb/hr	40,667	57,245	50,773	49,849	49,592
Limestone Sorbent Feed, kg/hr	18,446	25,966	23,031	22,612	22,495
Raw Water Withdrawal, gpm	5,321	10,072	8,244	8,046	7,953
Raw Water Withdrawal, m3/hr	1,209	2,288	1,872	1,827	1,806
Raw Water Consumption, gpm	4,227	7,733	6,346	6,196	6,126
Raw Water Consumption, m3/hr	960	1,756	1,441	1,407	1,391

Notes:

A. ΔP, ΔT for steam from STG to PCC is not accounted, similar to the Baseline report.

B. In the BBS Report Case 11, LP turbine exhaust steam quality is approximately 76%, which is lower than what is typically recommended by ST OEM (~90%). The LP turbine steam exhaust quality of ~91% for AKM cases is within the recommended range and consistent with the BBS Report Case 12.

C. Case-1A (and other AKM cases) auxiliary load for coal handling system was estimated based on Case 12 specific aux. load of 0.0009 kWh per 1 lb. of coal handled.

Exhibit A3-2: COE Analysis for Akermin Cases, Rev. Nov 2014

COE (2011$/MWh)	Case 11 No Cap.	Case 12 MEA	Case-1A	Case-2A	Case-2B
Fuel Cost	25.5	35.3	31.3	30.7	30.6
Power Plant Cap.	38.2	51.0	47.9	47.1	46.7
CO_2 Unit Capital	0.00	22.1	31.6	17.7	15.9
Variable Costs	7.74	13.2	11.7	10.9	10.7
Biocatalyst Cost	0.00	0.00	0.70	0.40	0.37
Fixed Costs	9.48	15.7	16.7	14.1	13.7
CO_2 TS&M	0.00	9.99	8.86	8.69	8.65
Total COE	**80.96**	**147.27**	**148.72**	**129.54**	**126.62**

Exhibit A3-3: Biocatalyst Cost Charge for Akermin Cases, Rev. Nov 2014

Biocatalyst Cost		Case-1A	Case-2A	Case-2B
Biocatalyst Charge	$/t$CO_2$	$0.79	$0.46	$0.43
CO_2 Capture Rate	tCO_2/year	3,605,040	3,546,132	3,532,864
Annual BC Cost	$/year	$2,852,755	$1,637,269	$1,528,302

Exhibit A3-4: Summary of Capital and Operating Costs (2011 USD x 1000, Rev. Nov 2014)

Item	BBS Case 11	BBS Case 12	AKM24 Case 1A	AKM24 Case 2A	AKM24 Case 2B
Capital Costs					
Total Plant Costs (TPC)	$1,089,771	$1,959,399	$2,129,053	$1,732,088	$1,673,904
Total Overnight Costs (TOC)	$1,348,443	$2,414,734	$2,624,865	$2,138,690	$2,067,803
Total As-spent Capital (TASC)	$1,529,135	$2,752,796	$2,992,347	$2,438,107	$2,357,295
Annual Operating Costs					
Fixed Costs	$38,829	$64,138	$68,429	$57,648	$56,085
Variable Costs	$31,688	$54,089	$50,654	$46,159	$45,437
Fuel Costs	$104,591	$144,504	$128,177	$125,825	$125,179

Exhibit A3-5: Performance and Cost Results, Rev. Nov 2014

	BBS Case 11	BBS Case 12	AKM-24 Case-1A	AKM-24 Case-2A	AKM-24 Case-2B
Gross Power Output, kWe	580,400	662,800	676,784	656,349	643,040
Auxiliary Power Requirements, kWe	30,410	112,830	126,786	106,356	92,989
Net Power Output, kWe	549,990	549,970	549,998	549,993	550,051
HHV Thermal Input, kWth	1,400,162	1,934,519	1,715,808	1,684,593	1,675,908
Net Plant HHV Efficiency, %	39.28%	28.43%	32.05%	32.65%	32.82%
Raw Water Withdrawal, gpm/MW net	9.7	18.3	15.0	14.6	14.5
Raw Water Withdrawal, m^3/MWh net	2.2	4.2	4.2	3.4	3.3
Raw Water Consumption, gpm/MW net	7.7	14.1	11.5	11.3	11.1
Raw Water Consumption, m^3/MWh net	1.7	3.2	3.2	2.6	2.5
CO_2 Generated, lb/h (Note)	957,272	1,322,604	1,172,296	1,150,968	1,145,035
CO_2 Generated, kg/h (Note)	434,218	599,933	531,753	522,079	519,388
Capture Efficiency		91.4%	91.2%	91.3%	91.7%
CO_2 Emitted, lb/h	957,272	113,446	103,346	99,612	94,679
CO_2 Emitted, kg/h	434,218	51,459	46,878	45,184	42,946
CO_2 Emissions, lb/MWh gross	1649	171	153	152	147
CO_2 Emissions, kg/MWh gross	748	78	69	69	67
CO_2 Emissions, lb/MWh net	1741	206	188	181	172
CO_2 Emissions, kg/MWh net	790	94	85	82	78
Total As-spent Capital, 2011$ x 1000	$1,529,135	$2,752,796	$2,992,347	$2,438,107	$2,357,295
Total As-spent Capital, 2011$/kW net	$2,780	$5,005	$5,441	$4,434	$4,286
Cost of Electricity, 2011$/MWh	$80.95	$147.27	$148.72	$129.55	$126.62
Levelized Cost of Electricity, 2011$/MWh	$102.65	$186.74	$188.57	$164.27	$160.55
% Increase in COE		82%	83.7%	60.0%	56.4%

Note: Based on assumed 100% carbon conversion.

Appendix 4: Evaluation of AKM24 CO_2 Capture System Capital Costs

A4-1. General

Equipment Cost - Based on design parameters provided by Akermin, WorleyParsons attempted to evaluate the reasonableness of the associated equipment pricing as developed by Akermin. This was done at a high level; primarily by extrapolating values from similar items in the WorleyParsons database. The effort was concentrated primarily on the high cost items.

Bare Erected Cost (BEC) – At this stage of a project, it is not uncommon to simply apply a multiplier to the equipment cost to arrive at the BEC. The multiplier is intended to capture the cost of the equipment installation along with the associated costs for normal foundations, structural steel, piping, electrical, instrumentation, insulation, and painting within a given envelope.

Costs for items such as piling, pipe rack and rack piping, major electrical and controls equipment, buildings, site-work, and demolition are generally not covered by these factors.

Akermin developed the BEC for each of the equipment items using Aspen Process Economic Evaluator. Using this program, the associated costs for the equipment installation, foundations, structural steel, piping, electrical, instrumentation, insulation, and painting are calculated for a given envelope. It is our understanding that Akermin used the default envelope as established in the program.

WorleyParsons looked at the ratios of the Akermin estimated BEC to equipment cost and compared these against our typical factors. While average factors are often used for a given type of equipment, the actual factors will vary based on the size and value of the specific item. The Akermin approach and the resultant ratios of BEC to equipment cost reflect this type of variation.

A4-2. Specific Findings / Results.

Towers (absorbers, strippers, DCC) – The towers were originally specified as SS, but were subsequently modified to CS with a SS lining. WorleyParsons extrapolated the cost of the towers from pricing previously developed for a similar project. As no reference pricing was available for the specified packing material, the cost for the packing material was calibrated based on the output from Aspen Process Economic Analyzer. On this basis, the costs for the towers appear to be within a reasonable range for the current stage of design.

Pricing for packing material can vary widely. While Akermin had a quotation for the packing from previous work, cost data for other column internals was not included for this scale of system. It's also notable that this cost data was not available in the BBS study for comparison with Aspen Process Economic Analyzer™ estimates for columns. Thus, it is recommended that the packing material and all other internals be re-quoted during the next phase of the project.

The BEC multipliers vary significantly; with the proper values decrease as the equipment price increases. Given the dramatic differences in the equipment pricing, driven primarily by the cost of the packing material, this is to be expected. Overall, the multipliers for the towers appear to fall within a reasonable range for type/value of the equipment.

Flue Gas Fans – The estimated cost of the fans appears to be within a reasonable range when evaluated against quotations from previous projects.

The BEC multipliers for the flue gas fans fall within a reasonable range for this type of equipment.

Vacuum Blowers – The pricing for the vacuum blowers was evaluated by WorleyParsons at this time as it cannot be adequately extrapolated from WorleyParsons database. A quotation was received from Man Turbo December 3rd, 2014 and the BEC has been re-estimated by Akermin. Unless specified, the basis for modeling and costing in this report is evaluated prior to receipt of the Man Turbo quotation.

Heat Exchangers – High level quotations were received for both the reboiler and the cross exchangers using water as the process fluid. Akermin inspected these estimates and reviewed the required surface area for the heat exchangers based on the AKM24 fluid properties (e.g., thermal conductivity, density, etc.). It was concluded that the heat exchanger sizing based on water gives an overestimate of surface area required. This analysis was used to determine the required number of units, and the unit costs were based on vendor quotes. The resultant pricing appears reasonable.

The vacuum blower condensers were not evaluated as they are relatively low cost items.

The BEC multipliers for some of the individual heat exchangers are significantly higher than average based on WorleyParsons' experience. However, at a summary level the average factor is closer to the expected range. Given that the heat exchangers are relatively small in terms of unit equipment cost and that there is a significant amount of relatively large diameter piping associated with many of these units, the summary level average factor seems reasonable.

Pumps – The estimated costs of the pumps appear to be within a reasonable range when evaluated against estimates/quotations from previous projects.

The BEC multipliers for the pumps are higher than what WorleyParsons would typically see as an average. The same is true when looking at the summary level average BEC factor. However, there is a significant amount of very large diameter piping associated with most of these units. The costs associated with this large diameter piping are more accurately captured in Akermin's calculations than by the use of average factors.

Tanks (solvent and steam cond pot) – The estimated cost of the tanks appears to be within a reasonable range evaluated against estimates/quotations from previous projects.

The BEC multipliers for the tanks fall within a reasonable range for this type of equipment.

Knock-out Drums (WKO) – The knock-out drums are specified as CS. Evaluation against quotations from a previous project would indicate the estimated pricing to be closer to SS than CS. The estimated costs of the knock-out drums varied more widely than those for the other equipment items; some in excess of 30% (up and down). It appears that some of this variation is a function of the pressure conditions. While the costs appear to be adequately covered for this stage of the project, further evaluation is recommended in the next phase of the project.

The BEC multipliers for the tanks fall within a reasonable range for this type of equipment.

Biocatalyst Recovery System (BRS) – Akermin has allotted $22.0MM Bare Erected Cost for the biocatalyst recovery system. Akermin explored several technologies based on budgetary estimates to select the lowest capital and lowest operating cost technology. Akermin plans to demonstrate the preferred option in lab-scale and bench scale tests within this project.

Interconnects – It is typical to include an allowance for interconnections to cover additional items such as pipe rack, rack piping, etc. that may not be captured in the envelopes established for the evaluation BEC for the individual equipment items. At this point in the cost development, it is recommended that an allowance of 5% of the BEC be added to the bottom line to account for interconnects. As the project progresses and layout drawings are developed, this allowance should be re-evaluated at a more granular level.

Appendix 5: Heat Exchanger Considerations

A5-1. Shell-and-Tube Exchangers

Shell-and-tube exchangers are widely used in industry. They can be custom designed for virtually any capacity and operating conditions, and any temperature and pressure differences between the fluids. They can be designed for special operating conditions, such as vibration, heavy fouling, highly-viscous fluids, erosion, corrosion, etc. They can be made from a variety of metal and nonmetal materials (graphite, glass, and Teflon) and in sizes from small (0.1 m^2, 1 ft^2) to very large (over 100,000 m^2, 10^6 ft^2) [A]. Shell-and-tube heat exchangers are extensively used as process heat exchangers in the petroleum-refining and chemical industries for a variety of applications. Heat transfer surface area of shell-and-tube exchangers per unit volume ranges from about 50 to 100 m^2/m^3 (15 to 30 ft^2/ft^3) [A], resulting in considerable requirements for space, support structure, and capital and installation costs. When the application allows shell-and-tube heat exchangers to be manufactured completely of carbon steel, such design may provide the most cost-efficient solution. However, overall shell-and-tube exchangers may be quite expensive compared to compact heat exchangers, such as plate heat exchangers.

A5-2. Plate Heat Exchangers

The plate heat exchangers have replaced shell-and-tube exchangers in those applications where the operating conditions permit such use. Plate heat exchangers have much higher heat transfer coefficients, and are less prone to fouling than shell-and-tube types in the same service. For the equivalent cost of the exchanger, compact plate heat exchangers will result in more efficient heat transfer. Typical applications for plate exchangers would be low-pressure and low-temperature, single-phase heating and cooling, when fluids are not hazardous, a high pressure drop can be tolerated, and alloys are required for the fluids being handled. Advantages and disadvantages of plate heat exchangers can be summarized as follows:

Advantages	Disadvantages
Very compact design	Designs are proprietary – limited number of manufacturers
High heat transfer coefficients (2 – 4 times shell & tube designs)	Gaskets limit operating pressures and temperatures & require good maintenance
Expandable by adding plates	Typical design limits for -gasketed plate and frame type 180°C and 20 barg, -welded plate type up to 550°C and 54 barg. [B]
Ease of maintenance	Gasket compatible with fluids are not always available

[A] R. K. Shah and D. R Sekulib, University of Kentucky, Chapter 17, Heat Exchangers,

[B] Jeff Kerner, Alberts & Associates, Inc., Plate Heat Exchangers: Avoiding Common Misconceptions, Chemical Engineering, February 2009

Advantages	Disadvantages
Plates manufactured in many alloys	Poor ability to handle solids – due to close internal clearances
All connections are at one end of the exchanger	High pressure drop
Good temperature approaches (as close as 3°C [C])	Not suitable for hazardous materials
Fluid residence time is very short	Not suitable in vacuum service
No dead spots	Gasket-free types suitable for non-cycling services
Leakage (if it should occur) is generally to the outside – not between the fluids	All-welded types available only in stainless steel or higher-grade metals
Low fouling due to high turbulence	

Gasketed plate heat exchangers (plate and frame heat exchangers)

In a gasketed plate heat exchanger, the plates are clamped together in a frame, and a thin gasket (usually a synthetic polymer) seals each plate around the edge. Tightening bolts fitted between the plates are used to compress the plate pack between the frame plate and the pressure plate. This design allows easy dismantling of the unit for cleaning, and allows the capacity of the unit to be modified by the simple addition or removal of plates. A frame holds multiple plates, creating many parallel flow paths for each fluid. Corrugations on the plate increase strength and improve heat transfer. Advantages include large area at moderate cost, possible high heat-transfer coefficients, and small exchanger physical size for the area. The use of gaskets gives a degree of flexibility to the plate pack, offering some resistance to thermal fatigue and sudden pressure variations. This makes some types of gasketed plate heat exchanger a good choice as a steam heater for instantaneous hot water supply, where the plates will be exposed to a certain amount of thermal cycling. The limitation in the use of the gasketed plate heat exchanger lies in the operating temperature range of the gaskets, which places a restriction on the steam pressure that may be used on these units.

Brazed plate heat exchangers

In a brazed plate heat exchanger, the plates are brazed together (normally using copper or nickel) in a vacuum furnace. Brazed plate heat exchangers were developed to provide more resistance to higher pressures and temperatures at a relatively low cost. Unlike the gasketed unit, the brazed plate heat exchanger cannot be dismantled. If cleaning is required it must be either back-flushed or chemically cleaned. These units come in a standard range of sizes, consequently oversizing is common. While the brazed heat exchanger has a more robust design than the gasketed type, it is also more prone to thermal fatigue due to its more rigid construction. Brazed heat exchangers

[C] Johan Gunnarsson, Alfa Laval Lund AB, Iain Sinclair and Francisco J. Alanis, AspenTech UK Ltd., Compact Heat Exchangers: Improving Heat Recovery, Chemical engineering, February 2009 are more suitable (and primarily used) for applications where temperature variations are slow, such as in space heating. They may also successfully be used with secondary fluids that expand gradually, such as thermal oil.

Welded plate heat exchangers

In a welded plate heat exchanger, the plate pack is held together by welded seams between the plates. The use of laser welding techniques allows the plate pack to be more flexible than a brazed plate pack, enabling the welded unit to be more resistant to pressure pulsation and thermal cycling. The high temperature and pressure operating limits of the welded unit mean that these heat exchangers are more suited to heavy duty process industry applications. They are often used where a high pressure or temperature performance is required, or when viscous media such as oil and other hydrocarbons are to be heated.

A5-3. Gasketed vs. Gasket-Free Plate Exchangers

Standard, gasketed plate-and-frame heat exchangers now routinely are available with elastomeric seals that can be used up to 180°C. Maximum design pressures for gasketed plate heat exchangers can reach in excess of 20 barg. In petrochemical and petroleum-refinery applications, gaskets frequently cannot be used because aggressive media result in a short lifetime for the gaskets, or because a potential risk of leakage is unacceptable. In these cases, all-welded compact heat exchangers without inter-plate gaskets should be considered. Operating conditions for gasket-free plate heat exchangers can be up to 550°C and pressures up to 54 barg. Gasket-free types should not be used for fluids that contain solids or tend to foul, since for most of them, the sealing methods used do not allow opening of the heat exchanger for inspection or cleaning. Typical applications for gasket-free types are clean fluids in non-cycling services requiring compactness and efficiency, and where design temperatures and pressures exceed the capability of gasketed types. Because all-welded heat-exchanger plates cannot be pressed in carbon steel, plate packs are available only in stainless steel or higher-grade metals. Traditional all welded heat exchangers with square/rectangular plates may suffer from thermal and pressure fatigue due to weaker corner welds that may fail in dynamic processes.

The gasketed plate heat exchanger is often the most efficient solution. The cost of an all-welded compact heat exchanger is higher than that of a gasketed plate heat exchanger. Nevertheless, in cases where gaskets cannot be used, all-welded compact plate heat exchangers can be a practical alternative to shell-and-tube heat exchangers.

A5-4. Reboiler Application Considerations

The steam heat exchanger market (such as reboiler application) was dominated in the past by the shell-and-tube heat exchanger. The design features and typical applications of the shell-and–tube type reboilers can be summarized as follows [D]:

[D] KLM Technology Group, Practical Engineering Guidelines for Processing Plant Solutions, Rev. 1, Aug 2013

Stab-In (Internal)	Least expensive type. They are limited in size by the physical space available inside the column and are not suitable for viscosities above 1 cP.
Kettle	Applicable when a high turndown or a high quality vapor is required. They are also used when large heat transfer surfaces are needed. Kettle reboilers are expensive due to the shell design, but are able to handle large differences in temperature between the fluids due to their U-tube design.
Vertical Recirculating Thermosyphon	Applicable when process rates are fairly constant, the viscosity of the fluid is low and the column height can be increased to accommodate the head requirements. Their operation requires a fixed static head. Vertical Thermosyphon reboilers are generally the least costly heat exchanger type (excluding stab-ins) due to their high heat transfer rates and low fouling tendencies.
Horizontal Recirculating Thermosyphon	Applicable when process rates are fairly constant, the viscosity of the fluid is low and the column height cannot be increased to accommodate the head requirements. Their operation requires a fixed static head.
Once Through	Applicable when the feed to the exchanger cannot be recirculated. The orientation can be horizontal or vertical. This design provides a low residence time on hot surfaces which is important in some applications. This design has a very narrow range of flows in which operation is stable.
Forced Circulation	A pump moves the fluid through the exchanger. Applicable when handling viscous liquids or a particulate-laden liquid, or when it is desirable to heat the liquid and then carry out the vaporization downstream of the exchanger. Any arrangement of shell-side or tube-side boiling, vertical or horizontal may be used.

Plate heat exchangers are suited for steam heating applications. In these applications, a plate heat exchanger may permit both the condensing and sub-cooling of condensate within a single unit. The following list describes several types of compact heat exchangers that have found some application as reboilers, and concerns/issues related to their design and application.

Plate-and-frame. Reboiler service complicates design. Momentum change effects in the parallel flow paths can require extensive design work or even modifications after initial results are checked in the field. While inconvenient, modifications are much simpler than for most other types of exchangers. Other disadvantages may include the need to have a pumped system and materials selection for the gaskets.

Welded plate. Such exchangers eliminate the gaskets of the plate-and-frame. However, the welded plate pack can't be dissembled for cleaning. Welded-plate exchangers are only suitable for clean services. Complex welded-plate exchangers also tend to suffer from thermal expansion problems. Because the plates usually are long, differential thermal expansion can create large stresses. Welded-plate exchangers can provide true counter-current flow. They serve as reboilers in some cryogenic and ultra-clean applications. New derivatives can act as cross flow exchangers. These often feed the process fluid in from edges 90° from each other. Along with simpler plate geometry, this creates an exchanger that possibly can be hydro-blasted clean. A limited number of reboilers have used this newer design.

Spiral plate. These exchangers wrap a long continuous channel into a spiral — most often to provide cross flow but it's possible to create a true counter-flow reboiler, as well. Variants include both welded and flange-gasket units, as well as gravity-flow and pumped-flow versions. Advantages include surface areas that are very large for the exchanger size and high heat-transfer coefficients. Spiral plate exchangers excel in services containing solids — and often are the exchanger of choice for such systems. Also, flange-gasket designs are typically relatively easy to clean. Properly laid out, spiral plate exchangers can tolerate fairly large temperature variations without excessive thermal stress. The main disadvantage is usually cost, especially for the flanged versions. The large flanges, as well as fabrication requirements, can make this type the most expensive option.

Spiral tube. Such exchangers run a coil of tube from a distribution manifold to a collection manifold. The tube-and-manifold assembly is inserted into a shell or can. The design easily accommodates thermal stresses. The availability of bendable tubes in the correct materials may limit fabrication. Spiral tube reboilers often are very small and used in applications where fabrication limitations make other types impractical.

Some manufacturers offer plate heat exchangers that are specifically designed for steam heating service. These steam-heating plate exchangers have large ports, short channel lengths and deep plate-pressing depths that are designed to address the following potential issues.

1. High steam velocity in the port can cause erosion and noise problems. Steam velocities in excess of 100 m/s should be avoided [B].
2. Very high heat-transfer coefficients encountered when using plate heat exchangers in steam heating service can result in small heat-transfer areas and therefore relatively small plate packs. As a result, the fluid to be heated may experience an excessive pressure drop, and the heat exchanger will have to be oversized (typically by adding plates in parallel) to keep the water-side pressure drop within specified limits. This can add unnecessary surface area and cost.
3. Small volume in the plate channel can lead to "plugging" as the steam present in the channels rapidly condenses and forms a vacuum. Vacuum formation followed by condensate build-up can create repeated water hammer, which can damage the heat exchanger and downstream equipment. An example of such failure of a welded plate reboiler is reported in reference [E], where a welded plate reboiler for a CO_2 stripper column has proven to be sensitive towards steam/water hammer, which subsequently resulted in micro-cracking of the heat exchanger internals.

A5-5. Work with Commercial Suppliers

[E] Vibeke Anderssona, Kristina Wittmeyerb, Oddvar Gorseta, Yolandi Mareeb, Knut Sandena, GHGT-11, Operational Experience and Initial Results from the First Test Period at CO_2 Technology Centre Mongstad, Published by Elsevier Ltd, 2013

Based on communications with commercial suppliers, plate-and-frame type heat exchangers have been recommended for cross flow and reboiler applications of the AKM24 system, and heat exchanger spec. sheets, drawings, weights, dimensions and other thermal and mechanical data, and budgetary pricing [F] have been obtained and utilized in this TEA report for the AKM24 design cases.

[F] Jennings Alberts, Inc., WorleyParsons: HX-301 Cross Exchanger & REB-301 Reboiler, Alfa Laval Heat Exchangers, 9-25-2014.